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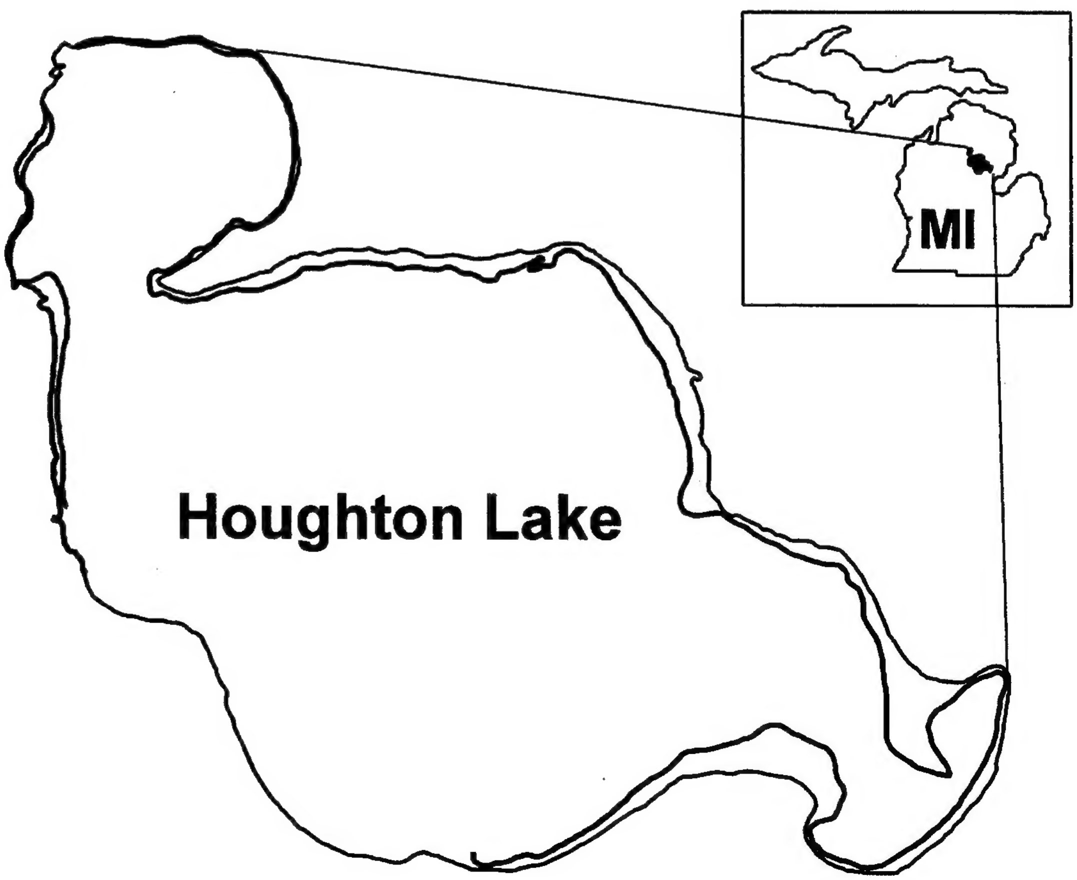
Aquatic Plant Control Research Program

Management of Eurasian Watermilfoil in Houghton Lake, Michigan: Workshop Summary

Kurt D. Getsinger, Angela G. Poovey, William F. James, R. Michael Stewart, Michael J. Grodowitz, Michael J. Maceina, and Raymond M. Newman

September 2002



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by Kurt D. Getsinger, Angela G. Poovey,
R. Michael Stewart, Michael J. Grodowitz

Environmental Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

William F. James

Eau Galle Aquatic Ecosystem Research Facility
P.O. Box 237
250th Street @ Eau Galle Dam
Spring Valley, WI 54767

Michael J. Maceina

Department of Fisheries and Allied Aquacultures
Auburn University
Auburn, AL 36849

Raymond M. Newman

Department of Fisheries, Wildlife, and Conservation Biology
University of Minnesota
1980 Folwell Avenue
St. Paul, MN 55108

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Detroit, MI 48226-2575

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Preface

The work reported herein was conducted as part of the Aquatic Plant Control Research Program (APCRP). The APCRP is sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE), and is assigned to the U.S. Army Engineer Research and Development Center (ERDC) under the purview of the Environmental Laboratory (EL), Vicksburg, MS. Funding was provided under Department of the Army Appropriation No. 96X3122, Construction General. Support was also provided by the U.S. Army Engineer District, Detroit, coordinated through Mr. Charles Uhlarik, Detroit District. The APCRP is managed under the Center for Aquatic Plant Research and Technology (CAPRT), Dr. John W. Barko, EL, Director. Mr. Robert C. Gunkel, Jr., EL, was Assistant Director, CAPRT. Program Monitor during this study was Mr. Timothy R. Toplisek, HQUSACE.

The Principal Investigator of this work was Dr. Kurt D. Getsinger, Environmental Processes Branch (EPB), Environmental Processes and Engineering Division (EPED), EL. This work was conducted and the report prepared by Dr. Getsinger and Ms. Angela G. Poovey, EPB; Dr. William F. James, EPB, Eau Galle Aquatic Ecosystem Research Facility, Spring Valley, WI; Mr. R. Michael Stewart and Dr. Michael J. Grodowitz, Aquatic Ecology and Invasive Species Branch, Ecosystem Evaluation and Engineering Division, EL; Dr. Michael J. Maceina, Auburn University, Auburn, AL; and Dr. Raymond M. Newman, University of Minnesota, St. Paul, MN.

Technical reviews of this report were provided by Ms. Diana Klemans, Michigan Department of Environmental Quality, Lansing, MI; Dr. John Madsen, Minnesota State University, Mankato, MN; and Dr. Craig Smith, Haslett, MI. Ms. Klemans also assisted with site selection and coordination for the workshop. Mr. Jim Scott and his staff at the Ralph A. MacMullan Conference Center were helpful in coordinating the workshop. Thanks is also extended to the members of the Houghton Lake Improvement Board, particularly Mr. Richard Pastula and Mr. James Deamud, and the other workshop participants (listed in Appendix A), without whom this workshop and report would not have been possible.

This work was performed under the general supervision of Dr. Edwin Theriot, Director, EL; Dr. Richard E. Price, Chief, EPED; and Dr. Terrence M. Sobecki, Chief, EPB.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC. COL John W. Morris III, EN, was Commander and Executive Director.

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Summary

Houghton Lake is the largest inland water body in Michigan, and as such, is a major ecological and recreational resource for the region. Results of a survey conducted in October 1999 indicated that over 4,000 ha of the lake had become infested with the exotic submersed plant Eurasian watermilfoil (*Myriophyllum spicatum* L.). Local concern regarding the problems associated with the Eurasian watermilfoil infestation centered on its future impact on recreational opportunities, fish and wildlife resources, and ecological health of the lake. In 2001, the U.S. Army Engineer District, Detroit, was tasked by Congress to assist the Houghton Lake Improvement Board (HLIB) in the development of a draft plan for managing Eurasian watermilfoil on the lake. Therefore, a workshop was held to review operationally viable techniques and discuss environmentally sound options for managing Eurasian watermilfoil in Houghton Lake. Management options considered included the use of chemical herbicides currently registered in the state of Michigan; the use of the milfoil weevil, a biocontrol agent; the use of mechanical harvesters; and an integration of these techniques. In addition, impacts to water quality and fish and wildlife resources were considered. The objective of this report is to summarize and present information from the workshop and other sources that will provide guidance for the environmentally sound management of Eurasian watermilfoil in Houghton Lake.

Conventional mechanical control techniques could theoretically be used to control all actively growing milfoil beds in Houghton Lake. Conventional mechanical harvesting systems include a harvester, a transporter (optional), an onshore conveyor, and trucks. However, due to the acreage involved, the low areal production rates of these systems, and the regrowth of harvested milfoil plants in 4 to 6 weeks, treatment by this technique will probably be limited to small high-use areas (e.g., boat lanes, marinas, boat launches, etc.) and control of free-floating plant fragments in open water. In addition, two-thirds of the Houghton Lake shoreline is negatively impacted by extensive windrows of plant fragments. Several nonconventional mechanical vehicles could be effective in removing plant fragment masses from shallow shoreline areas. Theoretically, a fleet of these amphibious vehicles could be configured to perform a similar plant fragment collection and transport operation in shallow-water areas as conventional mechanical harvester systems can perform in open-water areas; however, these vehicles would have to be tested and demonstrated on Houghton Lake.

Biological control techniques focused on the milfoil weevil, which is highly specific to watermilfoils. Surveys conducted on Houghton Lake in summer 2001 indicated the milfoil weevil is present throughout the lake at all sites surveyed, including the middle of the lake. Two factors are essential to effective biological control of weeds: adequate densities of control agents and proper target weed response. Many lakes fail to develop high or persistent weevil populations and thus do not exhibit control. Given sufficiently high and persistent weevil populations, declines are likely; however, when and where weevil populations will reach sufficient densities or when or where declines and suppression will occur cannot be currently predicted. Successful biological control results in a suppression of the pest plant, not its elimination. Because of the potentially cyclical nature of control and the lower predictability of control temporally, biological control is most useful for long-term control in lower priority sites and over large areas where other management actions would be less feasible or cost effective. High-priority areas, where effective and rapid control is needed (e.g., boat channels, swimming beaches, docks), should be managed with other approaches.

Chemical control techniques focused on both contact and systemic aquatic herbicides that were registered in the state of Michigan. With aquatic herbicides, species-selective control is important; the population of the invasive Eurasian watermilfoil can be significantly reduced while limiting negative impacts on the desirable native plant community. Contact herbicides appropriate for controlling Eurasian watermilfoil are diquat and endothall. Diquat can be used in small areas that may need immediate relief, such as swimming areas, docks, and boat-launching areas. Endothall can be used in block treatments ($\leq$20 ha), which would be low-dose applications and conducted as a demonstration. Systemic herbicides for control of milfoil are the low-volatile butoxyethyl ester of 2,4-D and fluridone. Treatment strategies using 2,4-D to control milfoil in larger areas of the lake ($\geq$ 20 ha) would include integration with diquat applications, mechanical harvesting, and biocontrol techniques. Fluridone can be used as a whole-lake treatment of milfoil; using low-dose application methods that have been verified in other Michigan lakes, widespread milfoil control could be achieved for several years using fluridone without significant environmental impacts.

Ecological considerations of the invasive Eurasian watermilfoil were potential impacts to the nontarget plant community, water quality, fisheries, and wildlife and impacts associated with viable milfoil management techniques. Invasions of exotic species such as Eurasian watermilfoil can dramatically change the macrophyte community structure, leading to changes in water quality and trophic structure. The formation of dense surface canopies by Eurasian watermilfoil leads to disruption of dissolved oxygen exchange, the development of low dissolved oxygen and/or anoxia below the canopy, enhanced nutrient recycling, and strong vertical gradients in pH and temperature. These changes may lead to physiological stress to the invertebrate and fish community. Moreover, there are trade-offs in water quality (both negative and positive) that must be considered when developing an aquatic macrophyte management plan with respect to the overall feasibility of application of a particular control

technique or suite of techniques. It is recommended that a water quality monitoring program be implemented in conjunction with an aquatic macrophyte control plan. Sound decisions regarding watershed rehabilitation to improve water quality and promote native macrophyte community persistence can then be made.

Houghton Lake has had in the past and currently contains valuable fish and wildlife resources. The fish and wildlife working group recommended that aquatic management plans should focus on maintaining natural habitats and attempting to reestablish aquatic vegetation. Although the impacts of the invasive species Eurasian watermilfoil should be curtailed, there are still much concern and debate in the local fish and wildlife community surrounding the type and level of control techniques available for managing the plant in Houghton Lake. Specific recommendations from the fish and wildlife group to manage Eurasian watermilfoil included conducting small (4- to 40-ha (10- to 100-acre)) test plots using the aquatic herbicides 2,4-D, diquat, and/or endothall, intensively stocking the milfoil weevil, and using mechanical harvesters to provide boat lanes near boat launches. This group was opposed to a whole-lake fluridone treatment. In addition, other biocontrol options such as fungus and pathogens should be explored. Moreover, fish-aquatic plant relations in Houghton Lake should be examined in detail as very little fishery data exist for a lake of this size. Both creel survey and fish data need to be collected with fish population assessments made in both vegetative and unvegetated areas of the lake. A commitment to long-term monitoring/research should be implemented in which aquatic plant managers and fishery biologists need to coordinate their respective activities to collect accurate data to assist in the decision-making process (statewide).

It is clear that actions can be undertaken to greatly reduce the amount of milfoil in the system, and keep milfoil populations at a reasonably low level, while restoring and conserving the recognized benefits of a diverse native aquatic plant community. In order to achieve such a goal, it is imperative that a lake management plan be developed to address the short-term problems associated with the infestation for the next 1 to 3 years, followed by addressing the long-term reduction and continued control of milfoil in Houghton Lake over the next several decades. This plan should prioritize the most valuable resources and lake uses in order to design and implement activities for restoring and maintaining Houghton Lake in a healthy condition now and in the future. Proven techniques for controlling milfoil in an environmentally sound manner, including biological, chemical, and mechanical, and the potential integration of any or all of these techniques must be carefully reviewed and assessed. Specific guidance for viable milfoil control options in Houghton Lake has been provided in this report. Watershed management practices, including maintenance of shoreline property and lake level issues, should be reviewed and assessed to determine impacts of those processes on the implementation and success of milfoil control techniques applied to the lake.

1 Introduction

Background

At over 8,000 ha, Houghton Lake is the largest inland water body in Michigan and as such is a major ecological and recreational resource for the region. Results of a survey conducted in October 1999 (Pullman 2000) indicated that over 4,000 ha of the lake had become infested with the exotic submersed plant Eurasian watermilfoil (*Myriophyllum spicatum* L.), and dense surface mats of the plant had formed in some areas of the lake. Large portions of these mats would break loose and drift with the prevailing winds to become lodged on shorelines. Local concern regarding the problems associated with the Eurasian watermilfoil infestation, centered on its future impact on recreational opportunities, fish and wildlife resources, and ecological health of the lake, ultimately resulted in the formation of the Houghton Lake Improvement Board (HLIB).

The HLIB is composed of representatives of the Michigan Department of Environmental Quality (MI-DEQ), the Roscommon County Board of Commissioners, the Roscommon Drain Commission, and the Denton, Lake, Markey, and Roscommon Townships. The HLIB is a permanent governmental entity established to direct the process for the control and/or elimination of Eurasian watermilfoil in the lake, and to address the problems associated with other aquatic plant growth, swimmers itch, water quality, and any other activity that would lead to improving the quality of the lake.

In 2001, the U.S. Army Engineer District, Detroit, was tasked by Congress to assist the HLIB in the development of a draft plan for managing Eurasian watermilfoil on the lake. As part of that task, the District requested the services of the U.S. Army Engineer Research and Development Center (ERDC), a national research and development (R&D) laboratory. The Corps of Engineers Aquatic Plant Control Research Program (APCRP) is managed at the ERDC Environmental Laboratory, Vicksburg, MS, and for over 30 years it has supported R&D in the aquatic plant control arena throughout the United States, with extensive experience in studying the biology and management of Eurasian watermilfoil.

In response to the District's request, the APCRP sponsored a workshop, which was held at the R. A. MacMullan Conference Center near Higgins Lake, MI, 17 and 18 May 2001. In addition to selected ERDC scientists, participants in the workshop included national and regional aquatic plant management experts from government, academia, and the private sector, and representatives of the HLIB. Workshop participants are listed in Appendix A, and participants in the working groups are listed in Appendix B.

The workshop participants reviewed and discussed operationally viable techniques for managing Eurasian watermilfoil in Houghton Lake that can be used to develop environmentally sound options for managing this invasive plant. Management options considered included the use of chemical herbicides currently registered in the state of Michigan (both partial and whole lake scenarios); the use of the milfoil weevil, a biocontrol agent; the use of mechanical harvesters; and an integration of these techniques. In addition to identifying viable management options, consideration was also given to (a) the short- and long-term goals of aquatic plant management on the lake; (b) the historical and present nature of the aquatic plant community; (c) watershed and limnological factors that might influence management techniques; (d) ecological impacts associated with the use of management techniques, including fish and wildlife issues; (e) short-term versus long-term control of Eurasian watermilfoil; and (f) techniques designed to assess the efficacy of management options and recovery of the plant community.

Results from the workshop were used to prepare this report. In addition, pertinent information from other sources about the hydrology and ecology of Houghton Lake as it pertains to the management of Eurasian watermilfoil is also summarized and reported in this document.

Objectives

The objective of this report is to summarize and present information from the workshop and other sources that will provide guidance for the environmentally sound management of Eurasian watermilfoil in Houghton Lake. The management options described in this report represent techniques that can be implemented on an operational scale, with approval from appropriate state regulatory agencies. Furthermore, each management technique will be discussed in relation to effectiveness of control, cost of implementation, and potential environmental impacts. Finally, the information provided in this report can be used to develop a plan for the management of Eurasian watermilfoil in the lake.

2 Houghton Lake

Morphology, Hydrology, and Limnology

Houghton Lake, located in Roscommon County, is the largest inland water body in Michigan, covering a surface area of slightly more than 8,100 ha. The lake is elliptical in shape, with a length of 15.6 km and mean width of 5.1 km; widest fetch is 8.7 km (Figure 1). In conjunction with nearby Higgins Lake (3,888 ha), it forms the headwaters of the Muskegon River (Figure 2). Although quite large in area, Houghton Lake is also very shallow, with an average depth of 2.6 m and a maximum depth of 6.7 m. The central basin of the lake is bounded on the northwest by North Bay and the southeast by East Bay (Figure 1). The lake sediment consists primarily of sandy shoals and gravelly areas, with organic material and sand mixed in deeper water, and clay deposits in North Bay (Evenson and Hopkins 1973).

The Houghton Lake basin is of glacial origin and its watershed comprises approximately 48,560 ha. The watershed drains surrounding land that is relatively flat and low-lying with soils typical of an end moraine system, consisting of sandy glacial outwash soils, silts, and clay-rich ground moraine and marginal moraine soils (Pecor et al. 1973; Schrouder 1993). Water flows from Higgins Lake via a connecting body of water called "The Cut" into Houghton Lake, and the lake also receives water from seven smaller tributaries, drains, precipitation, and groundwater (Pecor et al. 1973; Schrouder 1993). Two large marsh complexes of approximately 1,000 ha each are located on the west shore of the lake. In the past, these marshes operated as northern pike spawning areas in the spring. They continue to support waterfowl habitat in the fall (Novy and Pecor 1973). Houghton Lake is both a water supply and recipient of water discharged from these marshes. In the early 1970s, lake volume turnover (water retention time) was reported as 1.2 years (Pecor et al. 1973). Lake elevation is maintained by the Houghton Lake Dam, and the legal level is established at 346.9 m above mean sea level. Impoundments established on several Houghton Lake tributaries (i.e. "The Cut," Backus Creek, and Denton Creek), have the potential to warm downstream water temperatures and decrease inflow into the lake due to increased surface area and evapotranspiration (Schrouder 1993).

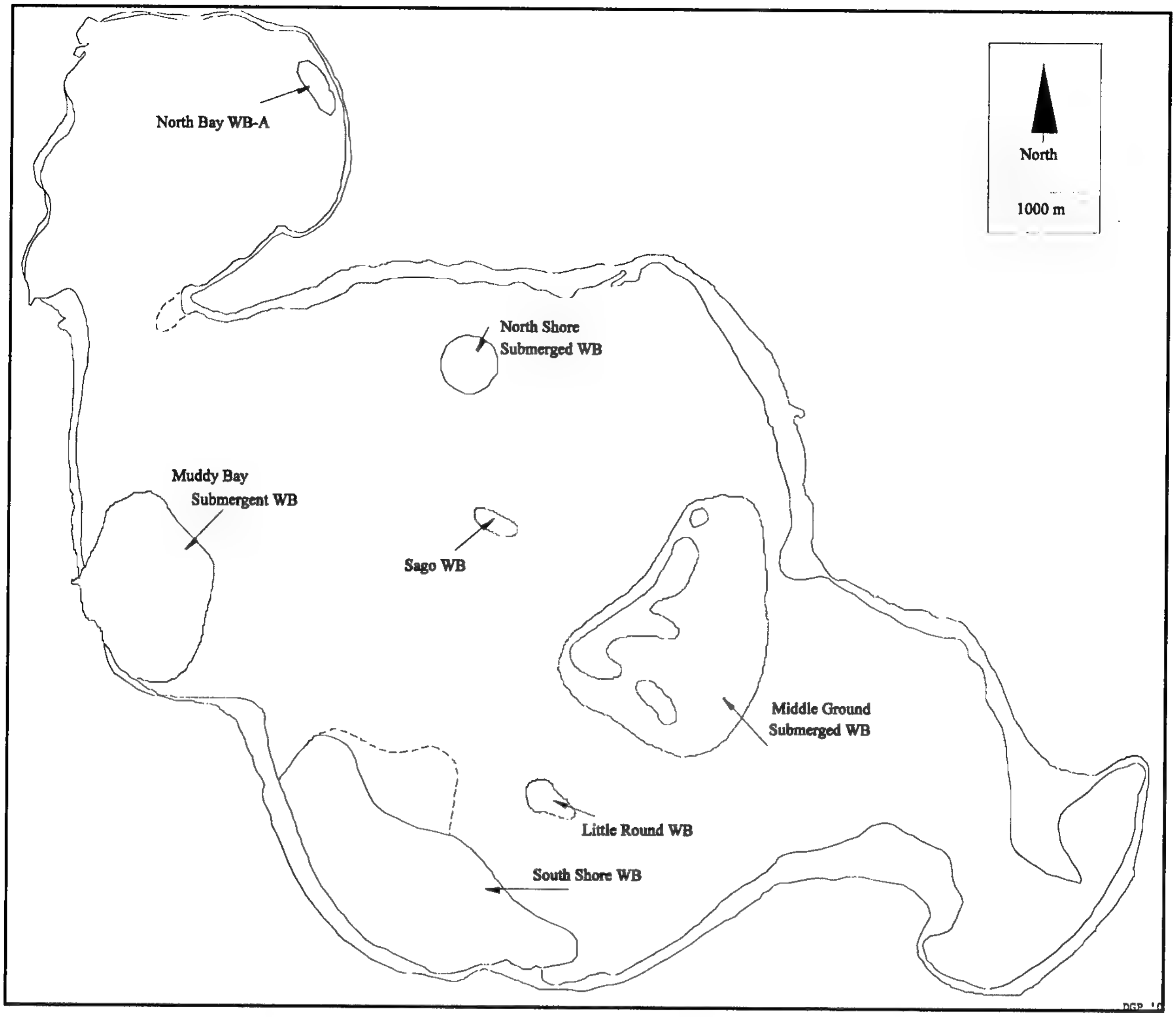

Figure 1. Houghton Lake, Roscommon County, Michigan. Submerged aquatic weed beds (WB) are indicated by circles drawn in the various lake bays (map redrawn after Evenson and Hopkins 1973)

Limnological studies from the early 1970s classified Houghton Lake as eutrophic (Pecor et al. 1973). However, the authors noted that this condition was not typical, in that the lake exhibited excellent water quality with none of the adverse conditions usually associated with eutrophy. Furthermore, these studies concluded that a good balance existed in the lake between the plant and animal communities, resulting in moderate plant growth and a productive sport fishery. Several wastewater treatment systems help to control nutrient inputs from surrounding homes.

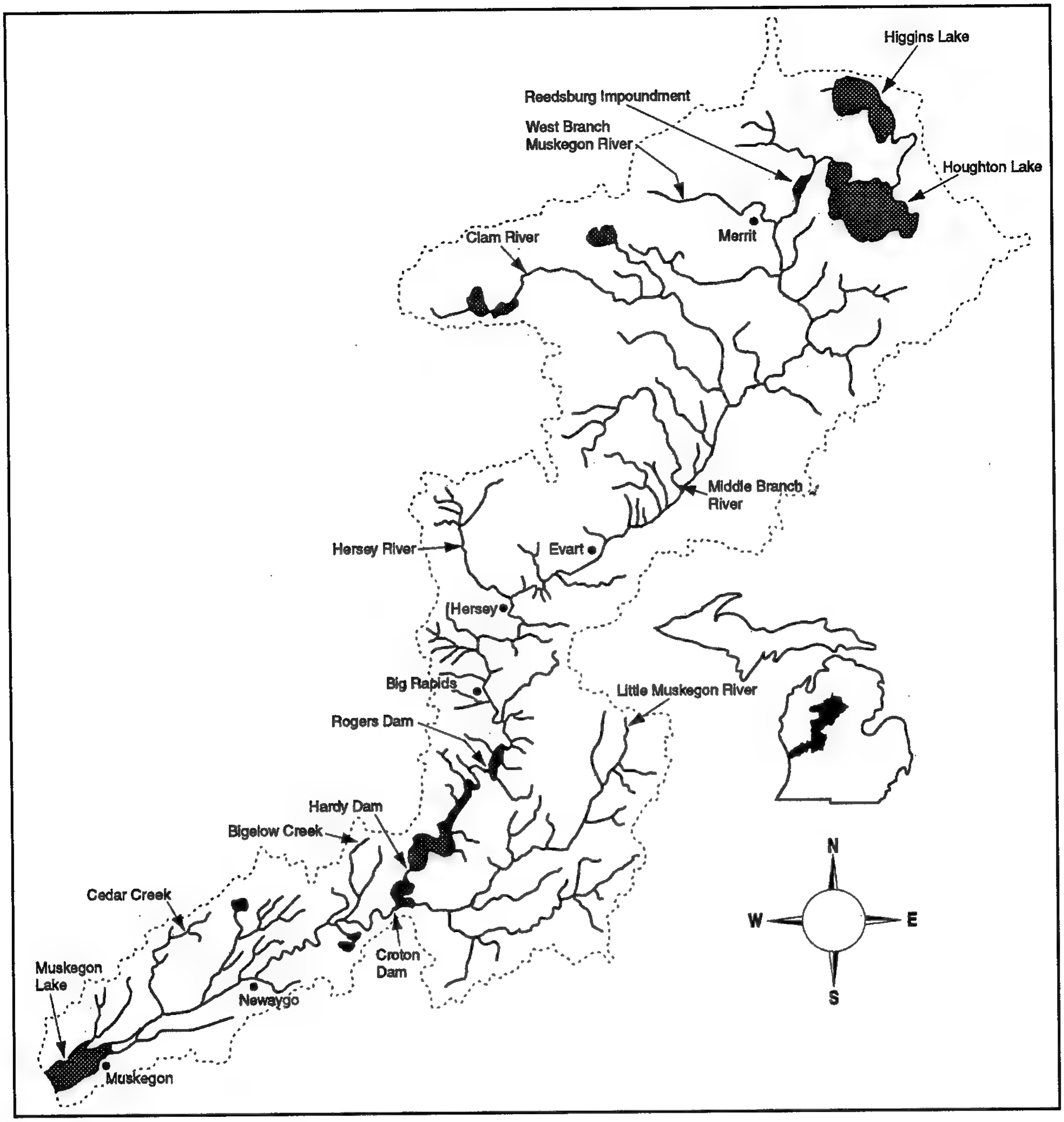

Figure 2. Major tributaries and landmarks in the Muskegon River watershed (map taken from O'Neal 1997)

Aquatic Plant Community: Past and Present

Historically, wild rice was the dominant emergent species in the lake; however, many of these prominent beds were significantly reduced due to rice cutting activities from the 1930s through the 1950s (Pirnie 1935; Evenson and Hopkins 1973). Wild rice stands continued to decline in the late 1980s, many of which were essentially absent by the early to mid-1990s (Ustipak 1995). Ustipak

(1995) suggested that the latest declines could be related to water level fluctuations, accumulation of chemical compounds in the lake sediment, increased wave action due to boat traffic and bulk heading of shorelines, nutrient deficiencies, and pathogens.

An extensive assessment of aquatic vegetation on Houghton Lake and its linkage with lakewide waterfowl populations was undertaken from 1972-1973 (Evenson and Hopkins 1973). This study showed that major areas of the lake were very productive with respect to submersed and emergent aquatic plants, and contributed to supporting thousands of waterfowl on the lake in 1972. The macroalga chara accounted for 72.5 percent of total plant production on the lake, while elodea, naiad, mud plantain, and various pondweeds were the predominant submersed vascular species observed.

Eurasian watermilfoil was not reported in the lake during a plant survey conducted in 1985 by the U.S. Army Corps of Engineers (U.S. Army Engineer District, Detroit, 1985). However, this nuisance species was reported as widespread and abundant (an estimated 4,047 ha impacted) in the lake by October 1999 (Pullman 2000). Eurasian watermilfoil had been reported as being present in Higgins Lake, upstream from Houghton Lake, and affecting native vegetation in that lake as early as 1997 (O'Neal 1997). Currently, it is estimated that Eurasian watermilfoil infests up to 4,000 ha of the lake, with dense stands occurring in some 2,000 ha.[1] These recent quantitative surveys also indicate an abundance of native submersed plant species present in much of the lake.

Although portions of the actively growing milfoil beds are located in the north bay and along the south shore, most occur in the middle, open-water region of the lake. Though these beds are problematic to navigation and certain ecological processes, they also serve as a source for plant fragment "rafts" that float into adjacent open-water areas, thereby creating problems there as well. However, possibly the most widespread and disruptive problem to lakeshore property owners and other nearshore water resource users has been the tremendous windrows of these plant fragments that are deposited by wind and wave action within the shallow-water shoreline zones. It is estimated that nearly two-thirds of the shoreline of Houghton Lake is negatively impacted by these extensive windrows of plant fragments. Examples of these negative impacts include physical disruption and shading out of native plant beds and benthic organisms, access denied to food items by shorebirds and other wildlife, foul odors and degraded water quality due to plant decomposition, and disrupted navigation and restricted access to boat launches and other shore-based facilities.

[1] T. McNabb, Personal Communication, 17 May 2001, ReMETRIX, Carmel, IN.

Natural Resources and Recreational Uses

Houghton Lake is a regional resource for recreation-based tourism, with nearly the entire 116-km shoreline developed with homes and resorts, most of which interface the lakeshore with bulkheads. The towns of Houghton Lake Heights, Houghton Lake, and Prudenville border the lake on its southern and southwestern shores. The Michigan Department of Natural Resources (MI-DNR) maintains three public access sites for boat launches, and there are several parks surrounding the lake in addition to the Houghton Lake State Campground located on the north shore. Beyond its importance for summer fisherman, swimmers, and boaters, the lake supports a winter ice fishery and provides abundant snowmobiling opportunities.

Fisheries in Houghton Lake have been managed since 1921, and the fish community appears stable, with no major changes noted since 1962 (O'Neal 1997). However, there was some concern about declining sport fishing catches in the lake in the early 1990s (Schrouder 1993). Primary game species include bluegill, walleye, northern pike, crappie, largemouth bass, smallmouth bass, and yellow perch, with walleye being the only species currently stocked. The lake also supports a significant transitory population of migratory waterbirds, including large concentrations of ducks, which have traditionally provided considerable waterfowl hunting opportunities.

3 Working Group Findings

Organization of Working Groups

During the workshop, four working groups were established to consider the following topics: (a) mechanical control techniques focusing on conventional harvesters; (b) biological control techniques focusing on the milfoil weevil; (c) chemical control techniques with aquatic herbicides registered in the state of Michigan; and (d) ecological considerations of the invasive Eurasian watermilfoil, and potential impacts to the nontarget plant community, water quality, fisheries, and wildlife associated with viable milfoil management techniques. Working group members were selected from the workshop participants, and were assigned to groups based upon their individual expertise in the subject topic areas.

Many participants contributed to the progression of information developed in several working groups (Appendix B). Because participants were from various agencies and backgrounds, the reader will likely note some divergence of views presented in this chapter. Initial findings of the groups were reviewed and discussed by all of the workshop participants in a plenary session. The findings of the working groups are summarized in this chapter. These findings do not necessarily represent the views and opinions of the U.S. Army Corps of Engineers. Mention of trade names in this report is not intended to recommend the use of one product over another.

Mechanical Control Techniques

Overview and objectives

Mechanical control techniques have been in use for centuries to battle nuisance growth of both terrestrial and aquatic plants. For purposes of this report, mechanical control techniques were classified based on how they eliminate the plant problems: (a) by inflicting physical damage on the problem plants in situ in the affected area, or (b) by physically removing all or portions of the problem plants from the affected area.

Techniques that inflict physical damage to plants in situ range from hand-operated implements to very specialized mechanized equipment. For example, in areas with sufficient water exchange, simply cutting rooted plants below the water surface, by either hand-operated or mechanized cutters, may result in transport of the problem plants from the affected area. Even in areas with insufficient water exchange to provide elimination of cut plant material, cutting in itself may lead to death and eventual decomposition for some species. However, for many typically problematic species (e.g., Eurasian watermilfoil), cut shoot material may continue to thrive if it is not removed by some secondary process.

Other mechanized equipment used for the in situ destruction of aquatic plants includes plant shredders, rototillers, and bottom rollers (Madsen 2000). Plant shredders are typically operated at or just below the water surface and are designed to kill floating plants or to remove the upper shoot material of submersed species. In contrast, rototillers are designed to extend to the bottom where they dislodge and cause significant physical damage to submersed plant root crowns and lower shoot material. Bottom rollers are an innovative type of mechanical control equipment for rooted submersed plants that function by physically compressing both the plants and the sediments within the treatment area. Bottom rollers up to 10 m long are available. During installation, one end is anchored as a pivot point, and an electric motor propels the roller repeatedly back and forth over an arc-shaped area. Though their treatment effectiveness is confined to their installation location, plant control is maintained with minimal human effort following installation.

For many aquatic plant control activities, plants must be removed from the site before the desired level of control can be achieved. Hand-pulling and removal is one of the most commonly used techniques by lakeshore property owners in the United States. Most effective when begun early (i.e., before biomass levels become excessive) and continued throughout the growing season, hand-pulling also provides some degree of species-selective control. For more widespread applications in open water and for strategic sites where excessive buildup of plants has occurred (e.g., ditches, canals, culverts, bridges), mechanized equipment is commonly used to remove the problematic plant growth. Clamshells or similar collection devices can be used from land-based vehicles at problem areas such as bridges or along ditches and narrow canals that have adjacent road access. For sites not accessible by normal land-based vehicles, clamshell collection devices can also be mounted on amphibious or water-based platforms. In all of these situations, collected material is either disposed of along the adjacent shoreline or placed into an attendant vehicle for transport to an alternate disposal site. One of the most commonly used mechanical systems for removing problem plants from canals and more open water areas is referred to as a conventional mechanical harvesting system. Though there are several manufacturers of conventional mechanical control systems (Table 1), all models have components that perform three basic functions: (a) cutting aquatic plants at some depth below the water surface, (b) collecting and removing the cut plant material from the water, and (c) transporting the collected plant material over water to a location for offsite disposal.

Table 1
Manufacturers of Conventional Harvesting Equipment for Aquatic Plant Control in Open Water Areas

Company	Address	Telephone and Fax	Web Site and E-mail	Products
Aquamarine	1444 S. Waukesha Waukesha, WI 53186	262-547-0211 phone 262-547-0718 fax	www.aquamarine.com weedharvesters@aol.com	Harvesters, trash skimmers, transporters, shore conveyors
Aquarius Systems	200 N. Harrison St. North Prairie, WI 53153	800-328-6555 phone 262-392-2984 fax	www.aquarius-systems.com info@aquarius-systems.com	Harvesters, trash skimmers, transporters, shore conveyors
Texas Harvesting	4443 Mammoth Grove Rd. Lake Wales, FL 33853	863-696-7200 phone 863-696-2922 fax	www.texasaquaticharvesting.com info@texasaquaticharvesting.com	Large-capacity harvesters, transporters, shore conveyors
United Marine International LLC	700-76 Broadway PMB 301 Westwood, NJ 07675	201-664-7500 phone 201-664-7501 fax	www.trashskimmer.com LShenman@aol.com	Harvesters, trash skimmers, transporters, shore conveyors

In order to help the HLIB determine the most appropriate applications of mechanical control techniques for aquatic plant problems in Houghton Lake, workshop participants were asked to provide the following:

a. Recommendations on use of mechanical control techniques that are applicable to primary aquatic plant problems in Houghton Lake, including established beds in open-water areas, floating plant fragment rafts in open-water areas, and windrowed plant fragment masses along the shoreline.

b. Time and cost estimates, where possible, for the different mechanical control techniques.

c. Information on the potential ecological impacts likely to result from implementing the different mechanical control techniques.

d. Recommendations on the potential for integrating the different mechanical techniques with applicable chemical or biological techniques.

Controlling milfoil beds in open water

Overview. Recent studies estimate up to 4,000 ha of Eurasian watermilfoil in open-water areas of Houghton Lake, with up to 2,000 ha of extremely dense growth (Pullman 2000; T. McNabb, personal communication). These actively growing weed beds not only have negative impacts in areas where they are established, they also are the source of the extensive free-floating rafts of plant

fragments in adjacent open-water areas and of the windrowed plant fragment masses affecting shallow, shoreline areas. Therefore, control measures must be implemented against these open-water milfoil beds.

Conventional mechanical harvesting systems. Conventional mechanical harvesting systems could be used to control Eurasian watermilfoil in actively growing beds. These systems include a harvester, a transporter (optional), an onshore conveyor, and trucks. Harvesters have U-shaped underwater cutter bars that cut plant shoots to depths up to 2 m below the water surface. Submersible conveyors attached to the cutter bars bring the cut plant material on board the harvester for temporary storage. However, due to the limited onboard storage capacity of harvesters, plant material must eventually be transported over water to an onshore conveyor, where it is offloaded onto an awaiting truck for upland disposal. If a dedicated transporter is included in the operation, the harvested load may be transferred to it for over-water transport to the shoreline offloading site. In this type operation, the harvester can continue with harvesting operations after the transfer is accomplished. If dedicated transporters are not included and the harvester must itself transport the collected plant material to the onshore conveyor, the production rate of the harvester will be greatly reduced. Conventional mechanical control techniques could theoretically be used to control all actively growing milfoil beds in Houghton Lake. However, due to the acreage involved, to the low areal production rates of these systems, and to the rapid regrowth of harvested milfoil plants in 4-6 weeks (Mikol 1985; Crowell et al. 1994), treatment by this technique will probably be limited to small high-use areas (e.g., boat lanes, marinas, boat launches, etc.).

Rototillers. Rototillers could be used to destroy root crowns of milfoil plants in high-use areas following mechanical harvesting operations. Destruction of root crowns by the rototiller should provide a significantly longer control time than would be provided by the harvest operation alone. Further, removal of the upper shoot material by the harvester prior to rototilling will reduce shoot entanglement of the rototiller and improve production rates of the rototilling operation.

Time/cost requirements. Production rates for mechanical harvesting operations are typically in the range of 0.4 to 0.8 ha per day per harvester. Actual rates depend on performance characteristics of the harvesting equipment (i.e., cutter bar width and storage capacity), water conditions and dimensions of the harvest site, over-water transport distance from the harvest site to the shoreline offloading site, and the harvestable plant standing crop in the treatment area (Sabol 1983; Sabol and Hutto 1984; Madsen 2000). Costs for harvesting operations are extremely variable and depend on these same factors. Per-hectare costs may range from as little as $500 per hectare to over $2,500 per hectare.

At the workshop, a cost estimate of $910 per hectare was calculated, based on some hypothetical conditions. Using this estimate, a single treatment of all actively growing milfoil beds in Houghton Lake with conventional harvesting equipment would cost approximately $3,640,000. However, extreme caution should be used in projecting this per-hectare cost estimate to either large-scale or

small-scale operations on Houghton Lake. It is also important to remember that treated sites would probably require a second harvest since plants usually grow back in 4-6 weeks.

Ecological impacts. Harvesting operations result in the immediate, non-selective removal of the upper shoot portions of targeted plant stands. In areas where excessive plant growth has led to degraded habitat and water quality, harvesting often provides temporary improvement in conditions. Harvesting dense stands of milfoil may promote good fish growth and allow predator fish to forage more effectively. However, other fish, turtles, and macroinvertebrates are themselves subject to becoming harvested, especially in dense plant stands that hinder their escape (Booms 1999). Contrary to widely held opinion, harvesting submersed plant species normally does not result in significant reductions in whole-lake nutrient levels (Madsen 2000). Harvesting canopy-forming species such as milfoil may provide some advantage to underlying native species, although this has not been reliably demonstrated in field studies. Nichols (1991) suggests that harvesting nontarget native species that reproduce by seed, regenerate poorly from fragments, or regrow slowly places them at a competitive disadvantage with plants with growth characteristics similar to milfoil. Fragment production by harvesting has often been mentioned as a detrimental consequence of this technique, since generated fragments can serve as a source for dispersal to new areas. However, several (Kimbel 1982; Nichols 1991; Madsen 2000) suggest that fragments generated by harvesting and other "artificial means" are not as viable as naturally occurring fragments, and therefore probably do not contribute significantly to in-lake dispersal and expansion of invasive plant species such as Eurasian watermilfoil.

Rototilling operations may have negative impacts on benthic organisms. In addition to temporary increases in turbidity, more long-term water quality impacts may follow from resuspension of sediment-bound plant nutrients, and perhaps even more significantly from resuspension of other immobilized sediment contaminants.

Integration with other techniques. Conventional harvesting and rototilling operations implemented for control of actively growing weed beds have the potential for integration with both chemical control and biological control techniques. Temporal integration of mechanical control techniques can be used to open boat lanes through dense weed beds while awaiting onset of large-scale impacts from systemic herbicide treatments or *Euhrychiopsis lecontei* releases. Mechanical control techniques can be spatially integrated with chemical control techniques by using mechanical harvesting for spot treatments in high water exchange areas, where contact herbicides would not be effective.

Nonconventional mechanical techniques. Several nonconventional mechanical control techniques were mentioned at the workshop that may have limited applicability to actively growing milfoil beds in Houghton Lake. Plant cutter boats could perform a similar cutting operation to mechanical harvesters, but without collecting the plant material. Innovative plant "shredder" systems and modified harvesters with onboard plant "chopper" systems were mentioned,

but to date only prototype systems have been manufactured. All three of these mechanized systems (cutters, shredders, and choppers) have higher production rates (= hectares treated per hour) than harvesting systems, since plant material is treated in situ and not transported to shore for upland disposal. However, before any of these three techniques can be recommended for operational use, an effective method for dealing with the remnant plant material will have to be determined. For plant remnants from cutter boats, methods for controlling free-floating or windrowed plant fragments other than mechanical harvesting will have to be demonstrated and implemented on large scale. For plant material processed by plant shredders and choppers, studies on the impacts of the processed plant material on water quality and other concerns should be undertaken.

Control of free-floating plant fragments in open water

Overview. Actively growing milfoil beds generate extensive free-floating fragment rafts in open-water areas of Houghton Lake. These free-floating fragment rafts are transient and ultimately are propelled by prevailing winds to shoreline areas where they are extremely detrimental. However, even before their arrival to nearshore areas, these extensive free-floating rafts create widespread negative impacts, including disruption of navigation, shading and physical injury to native plant beds, disruption of fisheries habitat, and access denied to foraging substrates by waterfowl. Therefore, control measures must be implemented to reduce the extent of the free-floating fragment rafts in Houghton Lake.

Conventional mechanical harvesting systems. Conventional mechanical harvesters can be used to control free-floating fragment rafts in Houghton Lake. The overall harvesting operation for fragment rafts will be similar to that previously described for actively growing weed beds.

Time/cost requirements. Production rates (=hectares/hour) for harvesting fragment rafts will be similar to rates for actively growing weed beds, with the potential that they may be slightly higher since the forward conveyor/cutter bar will not be extended as deeply into the water column during the plant collection process. Similarly, operational costs will probably be on the order of $160 to $380 per hectare. As for actively growing weed beds, the single factor most likely to decrease production rates and increase costs is over-water transport distance.

Ecological impacts. Potential ecological impacts are similar to those previously described for conventional harvesting operations for actively growing milfoil beds.

Integration with other techniques. There are no chemical control or biological control techniques directly applicable to free-floating plant fragment rafts. Therefore, integration is not possible. However, both biological and chemical control techniques have the potential for indirectly causing significant

reductions in the amount of fragment rafts by being operationally effective against the actively growing milfoil beds.

Nonconventional mechanical techniques. Workshop participants did not discuss other mechanical control techniques for collecting and removing free-floating fragments from open-water portions of Houghton Lake. However, it seems likely that any mechanical or naturally occurring process that could be used to centralize or spatially concentrate the fragments prior to their harvest/collection for transport to shore would greatly increase the efficiency of the overall effort. Therefore, it may be worthwhile to test and demonstrate if boats can be outfitted to push plant fragments to centralized collection sites, where harvesters could then collect and transport them to shore takeout sites. Similarly, it may be possible to design and construct an arrangement of strategically located floating booms in open-water areas to "passively collect" free-floating fragments as they are transported along prevailing wind circulation patterns in the open lake. Locations for these centralized collection sites, whether fragments arrive there by pusher boats or prevailing winds, should be selected in consideration of their over-water distance to onshore takeout sites.

Control of windrowed fragments along shoreline

Overview. Shallow-water littoral zones with depths less than 1 m extend several hundred meters offshore along much of the Houghton Lake shoreline. Following significant wind events, extensive windrowed plant fragment masses accumulate in these areas, creating possibly the most widespread and disruptive aquatic plant problem to lakeshore property owners and other nearshore water resource users. It has been estimated that nearly two-thirds of the shoreline of Houghton Lake is negatively impacted by these extensive windrows of plant fragments. Examples of these negative impacts include physical disruption and shading out of native plant beds and benthic organisms, access denied to food items by shorebirds and other wildlife, foul odor and degraded water quality during subsequent decomposition of these dead and dying fragment masses, and disrupted navigation and restricted access to boat launches and other shore-based facilities.

Applicable techniques. Conventional aquatic plant harvester systems cannot be used to control the plant fragment masses in the shallow-water and nearshore areas. Conventional harvester systems generally have a minimum operating draft of more than 1 m, and therefore, would not be able to collect fragment masses in these extensive shallow-water areas.

There are several nonconventional mechanical vehicles (Table 2) that should be tested for effectiveness in removing plant fragment masses from shallow shoreline areas. Tracked vehicles used by oil companies and others for navigating in marsh environments would possibly be effective. These "marsh buggies" have tall tracks that provide propulsion via ground contact in water depths to 1 m. In deeper water, these amphibious vehicles are propelled by paddle action of the tracks. A different type of amphibious vehicle is a modified

Table 2
Manufacturers of Equipment Applicable to Nonconventional Harvesting Operations of Windrowed Plant Fragments in Shallow-Water Areas Adjacent to Shorelines

Company	Address	Telephone and Fax	Web Site and E-mail	Products
Aquarius Systems	200 N. Harrison St. North Prairie, WI 53153	800-328-6555 phone 262-392-2984 fax	www.aquarius-systems.com info@aquarius-systems.com	Amphibious dredge
Dean Equipment	2240 Peters Rd. Harvey, LA 70058	800-437-4679 phone 504-367-3171 fax	www.deanequipment.com	Marsh buggies
Marsh Buggies, Inc.	2018 Engineers Rd. Belle Chasse, LA 70037	800-264-6868 phone 504-394-5052 fax	www.marshbuggies.com info@marshbuggies.com	Marsh buggies

barge propelled in shallow water by operation of four leglike appendages. Manufacturers indicate that these amphibious vehicles can be configured with numerous types of onboard plant collection devices (e.g., rakes, clam baskets, etc.) and/or with onboard containers for hauling collected plant material to shore takeout points for upland disposal. Theoretically, a fleet of these amphibious vehicles could be configured to perform a plant fragment collection and transport operation in shallow-water areas similar to that performed by conventional mechanical harvester systems in open-water areas.

Time/cost requirements. Production rates for collection and transport of plant fragments from shallow-water, shoreline areas by nonconventional mechanical control systems would have to be determined through demonstrations at Houghton Lake.

Ecological impacts. Potential ecological impacts from tracked vehicles include such things as detrimental impacts to underlying native plants and benthic communities and overall disruption and resuspension of nearshore sediments. However, both should be weighed against detrimental impacts of the decomposing plant fragment masses that this equipment would be attempting to remove.

Integration with other techniques. No other techniques are applicable to nearshore fragment masses. If demonstrations prove this type equipment to be effective, it could be used in shallow-water areas while other techniques are directed at controlling the source of the plant fragments in open-water areas.

Recommendations

The following are recommendations for mechanical control in Houghton Lake:

a. Use conventional harvesters in open-water areas for short-term control of actively growing milfoil beds for the following scenarios:

(1) For control in small areas where herbicides and/or biological controls cannot be used or where environmental conditions (e.g., high water exchange) prevent effective control.

(2) For creating boat lanes across extensive weed beds where treatment by less costly or longer term control measures is not applicable.

(3) For spot treatments within sensitive areas (e.g. water intakes).

b. Use conventional harvesters in open-water areas for collecting and removing free-floating plant fragments. Overall effectiveness of this type operation may be increased by placement of "fragment traps" along prevailing wind paths to concentrate fragments and prevent them from entering shallow-water areas inaccessible to conventional harvesters.

c. Test and demonstrate increased production rates of the "larger-than-normal-sized" conventional harvesters for controlling actively growing milfoil beds and free-floating plant fragments.

d. Demonstrate the use of amphibious vehicles and other custom nonconventional equipment for collection and removal of plant fragment masses in shallow-water, nearshore areas.

Biological Control Techniques Using the Milfoil Weevil

Overview and objectives

Biological control is "the use of parasitoid, predator, pathogen, antagonist, or competitor populations to suppress a pest population, making it less abundant and thus less damaging than it would otherwise be" (Van Driesche and Bellows 1996). The use of pathogens (primarily fungi) to control Eurasian watermilfoil is under investigation (e.g., Shearer 1996), but effective operational formulations have not yet been developed. Grass carp (*Ctenopharyngodon idella*) are effective generalist herbivores used to control many aquatic plants, but they have a low preference for Eurasian watermilfoil (Pine and Anderson 1991) and will eliminate preferred native plants before controlling the milfoil (Madsen 2000). Thus, grass carp is not a desirable control agent for Eurasian watermilfoil. Moreover, introduction of grass carp is illegal in Michigan. Although several historical and recent surveys for classical biological control agents (agents that control the exotic plant in its native range) have been conducted (Buckingham 1998), no classical agents have been released from quarantine (Buckingham 1994, 1998); and it is unlikely that classical agents will be available in the near future. Most attention has been given to indigenous (native) and naturalized (established adventitious exotics) insects. Three native or naturalized species have been considered as potential Eurasian watermilfoil control agents: the moth *Acentria ephemerella* (Denis & Schiffermüller) (= *Acentria nivea* (Olivier)), a naturalized Pyralidae; the indigenous midge *Cricotopus myriophylli* Oliver; and the indigenous weevil *Euhrychiopsis lecontei* (Dietz) (= *Eubrychiopsis lecontei*) (e.g., Painter and McCabe 1988; Kangasniemi, Speier, and Newroth 1993; Creed and Sheldon 1995; Sheldon 1997a; Johnson et al. 2000). All three taxa are

present in the Midwest (Newman and Maher 1995; Scholtens and Balogh 1996; Creed 1998). Although all three taxa have potential to control milfoil (e.g., Johnson, Gross, and Hairston 1998; Johnson et al. 2000; Kangasniemi, Speier, and Newroth 1993), prior research (Creed and Sheldon 1995; Sheldon and Creed 1995; Creed 1998; Newman and Biesboer 2000) suggests that *E. lecontei* is the most promising control agent. Thus the remainder of this report will focus on the milfoil weevil (*E. lecontei*), although many conservation strategies to protect or enhance the weevil (Newman, Thompson, and Richman 1998) will likely enhance the other agents as well.

Milfoil weevil

The milfoil weevil is indigenous to North America and is broadly distributed across the northern states and southern Canadian provinces (Creed and Sheldon 1994a; Creed 1998; Tamayo et al. 1999). The native host plants of the milfoil weevil are northern watermilfoil (*Myriophyllum sibiricum*) and likely other native watermilfoils such as *M. verticillatum* (Creed and Sheldon 1994a; Newman and Maher 1995; Solarz and Newman 2001). The weevil is fully aquatic and spends the summer submersed on watermilfoil plants; in the fall adults move to shore where they overwinter in dry leaf litter along the shore (Newman et al. 2001). Adults in the fall and spring have fully developed flight muscles and have been observed to fly, but the extent of flight dispersal is unknown. After ice-out, from mid-March through May, adult weevils return to the water and feed on the top portions of watermilfoil plants (Newman et al. 2001). Once water temperatures reach 15 °C, females complete egg development and begin to lay eggs within 1 to 2 weeks (Mazzei et al. 1999). Females lay yellow eggs (ca. 0.5 mm diameter) singly on watermilfoil meristems at an average of two to four eggs per day (Sheldon and O'Bryan 1996b; Sheldon and Jones 2001). Larvae eat the meristem and bore down through the stem, occasionally venturing outside the stem for short (<2 cm) distances. Larvae will mine about 15 cm of stem to complete development (Mazzei et al. 1999) and will then move further down the stem (0.5 to 1 m from the apical meristem) where they bore a chamber to pupate. Development times depend on temperature; the minimum developmental threshold is 10 °C (Mazzei et al. 1999). Development from egg to adult takes 309 degree days (above 10 °C), and the upper developmental temperature is around 32-34 °C, with a maximum rate between 29 and 31 °C. At typical summer lake temperatures of 25 °C, eggs take about 5 days to hatch, larval and pupal development each take 7 to 8 days, and complete development to adults takes about 21 days. At typical summer temperatures in Minnesota, a maximum of four or five generations can be produced in one summer (Mazzei et al. 1999). Laboratory survival is high, ranging from 50 to 75 percent survival from egg to adult (Newman, Borman, and Castro 1997; Mazzei et al. 1999). More life history information is available online at http://www.fw.umn.edu/research/milfoil/milfoilbc.html

The milfoil weevil is highly specific to watermilfoils. Very little feeding has been reported on nonwatermilfoil plants, and weevils do not develop on these plants (Sheldon and Creed 1993). In oviposition choice tests with several

hundred females, only several eggs were laid on nonwatermilfoil plants (Solarz and Newman 1996, 2001). Female weevils will lay eggs and weevils will develop to adult on the native northern watermilfoil and *M. verticillatum* as well as Eurasian watermilfoil and will lay eggs on, but not develop on, the exotic parrot feather (*M. aquaticum*) (Solarz and Newman 2001). Egg laying rates are higher (two to five times) on the exotic Eurasian watermilfoil than on the native northern watermilfoil (Sheldon and Jones 2001). Development times and survival rates are as good as or better on Eurasian watermilfoil than the native hosts northern watermilfoil and *M. verticillatum* (Newman, Borman, and Castro 1997; Solarz and Newman 2001). Females reared on northern watermilfoil show no preference between Eurasian and northern watermilfoil, but females developed on or exposed to Eurasian watermilfoil for several weeks prefer to oviposit on Eurasian over northern watermilfoil (Solarz and Newman 1996, 2001). Although there may be a minor genetic component to plant preference, most of the response is environmental (exposure plant) (Solarz 1998). Thus Eurasian watermilfoil is the preferred host of weevils exposed to it, and Eurasian is as good a host as, if not better than, the original native hosts of the milfoil weevil.

Milfoil weevils in Houghton Lake

The milfoil weevil is native to Michigan (Creed 1998) and was reported from Houghton Lake in 2000, the first year in which efforts were made to locate the weevil. Surveys in summer 2001 indicated that the milfoil weevil was present throughout the lake at all sites surveyed, including the middle of the lake, 3.8 km from shore.[1] Currently, the size and abundance of the population are unknown, but it is clear that the weevil naturally occurs in the lake, is widespread, and is somehow able to disperse from shore to the middle of the lake. Dispersal was of some concern because there are few plants along the shoreline and weevils need to travel 400 to 800 m from shore to reach the milfoil beds.

Effectiveness

The milfoil weevil is effective at preventing growth of milfoil in laboratory aquaria and causing the plants to lose buoyancy and fall out of the water column (Creed, Sheldon, and Cheek 1992; Creed and Sheldon 1994b). In large outdoor tank experiments, weevil populations developed rapidly and caused significant declines in both viable aboveground biomass and root biomass (Newman et al. 1996). In addition, stem mining by the weevil caused reductions in both stem and root carbohydrates and reduced carbohydrate stores. This reduction in carbohydrate stores may diminish the ability of the plant to grow and compete the following spring. It also may be one mechanism for long-term declines (Creed and Sheldon 1995; Newman et al. 1996). The milfoil weevil has caused suppression of milfoil height and biomass in several field enclosure experiments

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[1] M. Hilovsky, Personal Communication, 2001, Enviro Science, Stow, OH.

(Creed and Sheldon 1995; Sheldon and Creed 1995). Moreover, the milfoil weevil has been associated with numerous milfoil declines (Creed 1998). Although many of these declines are poorly documented and cannot be directly related to weevil damage, 33 of 54 declines had weevils present and significantly more declines occurred within the range of the weevil than outside its range (Creed 1998).

There are a more limited number of declines associated with the weevil that have been well documented. The best example is Brownington Pond, Vermont (Creed and Sheldon 1995; Sheldon 1997b). Eurasian watermilfoil declined from dense levels in the mid-1980s (10 to 11 ha covered) to very low levels in 1989 (<0.5 ha). Subsequent increases in Eurasian watermilfoil (to much lower levels than historical) were met with increases in milfoil weevil populations and subsequent milfoil decreases of fourfold or more (Creed and Sheldon 1995). The suppression was documented for several more years through 1995; during this time milfoil never exceeded 65 g dry mass (dm) m^{-2} and increases in milfoil were suppressed with increased weevil populations (Sheldon 1997b). Declines associated with weevil activity or augmentations, though less well documented, have been reported in several other New England lakes (Sheldon 1997b).

In Wisconsin, Lillie (1996) reported a lakewide decline of Eurasian watermilfoil in 1993 and 1994 associated with the milfoil weevil in Fish Lake; milfoil coverage and biomass were reduced to half of previous levels. The decline persisted for 3 years, and then Eurasian watermilfoil returned to pre-decline levels (Lillie 2000). Although Lillie did not report weevil densities prior to the decline, weevil densities in Fish Lake increased from 7 m^{-2} in 1992 to 21 m^{-2} in 1993 (Mizner 1999). In 1995, the year before the rebound, weevil densities were quite low (<0.05 per stem, likely <5 m^{-2}) and declined to zero in late summer (Lillie 2000). Weevil densities subsequently increased with the increasing milfoil density; and a new decline may have been initiated, but no further sampling was conducted. Lillie (2000) suggests that declines and resurgence may be expected from weevil-milfoil interactions. Augmentation monitoring in Wisconsin suggested the occurrence of ten or more additional milfoil declines associated with weevil activity (Jester et al. 2000); however, longer term monitoring was not conducted.

In Minnesota, one decline of Eurasian watermilfoil has been directly linked to weevil activity; in Cenaiko Lake milfoil biomass declined from 120 g dm m^{-2} to 23 g dm m^{-2} in one season and remained suppressed to <16 percent of plant biomass for 4 years (Newman and Biesboer 2000; Newman, Ragsdale, and Biesboer 2001). This decline was associated with very high densities of weevils (initially 100 m^{-2}) that persisted throughout the summer and across years at densities ranging from 0.02 to 3 weevils per stem. This milfoil decline was accompanied by an increase in native plants (to 100 to 300 g dm m^{-2}) and a reduction in milfoil stem and root carbohydrates, which may have been factors in the persistence of the decline (Newman and Biesboer 2000). Declines have been noted in several other Minnesota lakes with moderate to high weevil densities; a decline has persisted in the shallower portion of one lake and is being maintained lakewide in another lake (Newman, Ragsdale, and Biesboer 2001). Several other lakes

have low to barely detectable weevil populations and show no indication of declines associated with milfoil weevils.

Several estimates have been made of weevil densities required to cause declines. In Brownington Pond, Vermont, densities of 1 per stem or 250 m^{-2} were sufficient to cause and sustain declines. Based on a summary of experimental and observational studies, Newman et al. (1996) suggested 200 weevils per m^{-2} or 2 to 4 per stem should result in significant declines. More recently, Newman and Biesboer (2000) suggested that 100 weevils per m^{-2} or1.5 per stem would be sufficient to control Eurasian watermilfoil, and analysis of the most recent data (Newman, Ragsdale, and Biesboer 2001) suggests perhaps even lower densities (25 m^{-2} or 0.25 per stem) may be sufficient to effect a decline. Factors limiting weevil density are discussed in the section "Predictability."

Stem mining reduces buoyancy, causing the plants to drop out of the water column and perhaps below the photic zone (Creed, Sheldon, and Cheek 1992; Creed and Sheldon 1995). This, in conjunction with damage to the vascular system, which reduces the ability of the plant to translocate nutrients and carbohydrates, may be important in reducing the competitive advantage of the milfoil and its ability to regrow the next spring (Creed and Sheldon 1995; Newman et al. 1996, Creed 2000). In addition, the wounding of the plant and deposition of frass may make the plant more susceptible to pathogen attack (Creed 2000).

Depth may also affect weevil density and effectiveness. Tamayo, Grue, and Hamel (2000) found that milfoil beds with weevils were shallower than beds without weevils. Jester et al. (2000) found that milfoil weevil abundance was negatively associated with depth. A greater distance from shore does not prevent weevil access to plants because Jester et al. also found that weevil abundance was positively correlated with distance from shore to the middle and deep edges of the plant bed, but was not related to distance to the shallow edge of the bed. Thus weevil populations may be higher in large shallow expanses of milfoil rather than steep shorelines with plants below the surface (Jester et al. 2000). Lillie (2000) found the highest densities of weevils and greatest damage in the shallow and middle portions of beds and much lower densities at the deep edges. Johnson et al. (2000) found weevil densities negatively correlated with lake depth and size and suggested that the milfoil weevil is more suited to smaller and shallower lakes rather than large deep lakes. Newman, Ragsdale, and Biesboer (1999) also found that weevil abundance was higher in shallower sites closer to shore, but this does not appear to be related to distance from shore. In Lake Auburn, highest densities were found at sampling stations within 40 m from shore and densities were typically much lower at 50 and 60 m from shore near the deep edge of the plant bed. In Smith's Bay of Lake Minnetonka, the highest weevil densities are found within 200 m from shore although weevils are commonly found at 370 m from shore and occasionally 585 m from shore. They have not been collected at the deepest (4-m depth) station 800 m from shore. Suppression of milfoil follows similar trends. For example, at Smith's Bay, Eurasian watermilfoil is barely detectable at the shallowest site (depth = 1.5 m) and has been replaced by native plants including northern watermilfoil

(Newman, Ragsdale, and Biesboer 2001). At the second shallowest site the weevil has also suppressed milfoil abundance, but at the deeper stations there is no evidence of control. Deeper plants may provide less refuge for the weevil than plants that approach the surface, both from fish predation and wave action. Deeper plants may also be less accessible to adults, which would need to dive to reach the plants.

Lastly, the competitive ability of native plants to replace milfoil biomass is also likely important (Newman, Thompson, and Richman 1998). Plant competitive ability is influenced by sediment nutrient content. McComas (1999) suggested that nuisance milfoil growth may be related to sediment exchangeable nitrogen (N). At high (>3 mg N per kg) nitrogen levels, Eurasian watermilfoil may have a competitive advantage over native plants that are more adapted to lower nitrogen levels. At levels below 2 mg N per kg, milfoil growth may be limited and the native plants may be able to compete. Sediment nutrients may also influence the ability of milfoil to recover from weevil damage (Creed 2000). In high-nutrient sediments the plant may recover and outgrow weevil damage, whereas in lower nutrient environments the plant may not be able to recover from weevil damage.

These studies indicate that the milfoil weevil can control Eurasian watermilfoil when sufficient densities of weevils persist throughout the summer and from year to year. Two factors are essential to effective biological control of weeds: adequate densities of control agents and proper target weed response (Newman, Thompson, and Richman 1998). Many lakes fail to develop high or persistent weevil populations and thus do not exhibit control. Factors that limit weevil populations must be identified and ameliorated (Newman and Biesboer 2000). Positive native plant community response is also likely important (Newman, Thompson, and Richman 1998). In several lakes where control was short term and not persistent (e.g., Fish Lake, Wisconsin; Lake Auburn, Minnesota) native plant abundance was low and dominated by coontail (Lillie 2000; Newman, Ragsdale, and Biesboer 2001) and an abundant rooted plant community did not replace the lost Eurasian biomass. In the best-documented examples of persistent decline, native plant communities have replaced the displaced milfoil biomass (Sheldon 1997b; Newman and Biesboer 2000). Factors that influence effectiveness will also influence predictability.

Predictability

Given sufficiently high and persistent weevil populations, declines are likely. However, many, if not the majority, of the sites investigated have failed to sustain sufficient weevil density to effect control. It currently cannot be predicted when and where weevil populations will reach sufficient densities nor when or where declines and suppression will occur (Creed 2000; Newman and Biesboer 2000). Both adequate agent densities and proper plant response are required for predictable control. Because plant community response and competitive interactions have been addressed previously and will likely be important for sustained control with any control technique, they will not be considered further.

Understanding factors limiting weevil populations will be critical to predictability, and these factors are addressed in the following paragraphs.

Overwinter habitat is required to sustain weevil populations. Adult weevils require dry sites with duff or leaf litter near the shore to overwinter (Newman et al. 2001). Jester et al. (2000) found that in-lake weevil densities were positively related to percent natural shore and negatively related to percent sand shore. Overwinter mortality, at least at good sites, does not appear severe, and in Minnesota overwinter survival typically ranged from 24 to >60 percent (Newman et al. 2001), comparable to overwinter survival of other beetles. In the Minnesota populations studied, in-lake factors appeared more important than overwinter conditions in sustaining populations (Newman et al. 2001); however, more whole-lake studies of overwinter success are needed.

In-lake factors are important because the rapid development times and multiple generations of the milfoil weevil should enable populations to build up throughout the summer even with low spring populations. Simulation modeling suggests that females need to lay eggs for at least 5 days (two eggs per day) to maintain a stable population, but increasing the egg-laying period to 10 days would result in an eightfold increase in the end of summer adult density (Newman, Ragsdale, and Biesboer 2001). At one lake in Minnesota, weevils disappeared from samples in July 1998 and were not found in the lake or in shoreline samples during the rest of 1998 or 1999. They reappeared in spring 2000, indicating successful colonization from elsewhere (Newman, Ragsdale, and Biesboer 2001).

Parasites and pathogens can limit insect populations (Newman, Thompson, and Richman 1998), but limited investigation suggests they are not affecting milfoil weevil populations in Minnesota. No parasitoids have been found, and although some milfoil weevils were infected with microsporidia and gregarines, the low rates and degrees of infection suggest they are not pathogenic (Newman et al. 2001).

Plant quality may affect weevil survival and reproductive success (Newman, Thompson, and Richman 1998; Creed 2000). Sufficient stem diameter for larval feeding and pupation has been suggested to be an important limiting factor (Sheldon and O'Bryan 1996b; Creed 2000), but this may often not be important in the field. Plant nutrients (nitrogen, protein, fatty acids) have been shown to affect survival and success of other aquatic weed biocontrol agents (e.g., Room 1990; Wheeler and Center 1996, 1997), and plant defenses may also limit agent success (Newman, Thompson, and Richman 1998). Although little is known of the food quality requirements of the milfoil weevil, Spencer and Ksander (1999) have shown considerable temporal and spatial variability in milfoil nutrient content and defensive chemicals. Solarz and Newman (2001) found that weevils reared as larvae on Eurasian watermilfoil were larger than weevils reared on northern watermilfoil. Sheldon and Jones (2001) showed that fecundity of milfoil weevils was much lower on the native northern watermilfoil than Eurasian watermilfoil, suggesting a difference in plant quality. In another study, weevils laid twice as many eggs on Eurasian than northern watermilfoil, and weevils

collected from Eurasian were larger than weevils collected from northern watermilfoil (Krueger and Newman 2001). Furthermore, egg-laying rate was positively related to female mass, suggesting that plant quality may have a big effect on fecundity both by affecting female mass and by affecting egg-laying rate. Less is known about response of weevils to different genotypes of Eurasian watermilfoil or milfoil plants reared on different sediment types. One experiment indicated significant differences in development time and survival related to plant genotype and sediment, but another experiment indicated no significant differences (Newman, Ragsdale, and Biesboer 1999, 2000). More investigation of the importance of plant quality is needed.

Water temperature affects weevil development rate and could limit weevil populations. Weevils will not develop in water cooler than 10 °C, and egg laying does not begin until the water approaches 15 °C (Mazzei et al. 1999). At cool temperatures of 19 °C, it takes about 32 days for weevils to develop from egg to adult, whereas at 27 °C complete development takes only 17 days. Spencer and Ksander (1999) note that cool temperatures in the Truckee River would limit weevil populations to two generations, making them less likely to control milfoil. Sustained water temperatures over 34-35 °C are likely lethal (Sheldon 1997b) and could reduce or eliminate populations.

As mentioned previously, water depth may be an important factor in success. Weevil densities appear lower in deep water or at the deep edge of plant beds, and the highest populations may occur in large beds in relatively shallow water (e.g., Jester et al. 2000; Johnson et al. 2000; Lillie 2000). This effect does not appear to be related to distance from shore or dispersal to the sites, but rather is a direct effect of depth. Deeper milfoil plants may be difficult for adults to reach, plants on the deep edge of the bed may be more subject to wave damage (and loss of larvae and adults), the water temperatures may be cooler, and deeper plants may harbor more fish or allow more efficient feeding by fish. In addition, deeper plants might be more difficult to control, as weevil larvae would mine a smaller proportion of their length.

Lastly, predation may be an important factor limiting control agent populations (Newman, Thompson, and Richman 1998; Creed 2000). Work in Vermont indicated that yellow perch (*Perca flavescens*) did not consume weevils and were not affecting weevil populations (Creed 2000). Newbrough (1993) found that bluegill sunfish (*Lepomis macrochirus*) would consume weevils in the laboratory, but did not observe any significant effect on weevils in field enclosure experiments. In Minnesota, Sutter and Newman (1997) found no weevils in yellow perch and black crappie (*Pomoxis nigromaculatus*) stomachs but found adults and a few larvae in sunfish (*L. macrochirus* and *L. gibbosus*) stomachs. They estimated that predation by high-density sunfish populations could limit weevil density. Subsequent observations in Minnesota suggest that sunfish predation may limit weevil populations. At some sites, weevil densities decrease rather than increase over the summer; in Lake Auburn, weevils disappeared from the lake for 1.5 years (Newman, Ragsdale, and Biesboer 2001). Most lakes without declines have high sunfish densities. The decline of milfoil in Cenaiko Lake followed a major decline in sunfish density (Newman and

Biesboer 2000); sunfish densities in 1992 were high and similar to other lakes with few weevils, but the next fishery survey in 1998 indicated a very low density of sunfish. The milfoil decline and high density of weevils were first detected in 1996, suggesting that the weevil population increased after the decline of the sunfish population. Fish exclusion cage experiments show that sunfish can limit weevils; weevil populations are higher in fish exclusion cages than in open cages in a lake with high sunfish density (Newman, Ragsdale, and Biesboer 2001). Lastly, the lower densities or absence of weevils at bed edges or in deeper water is consistent with higher fish predation on the more accessible plants. Currently it is not known if there is a threshold density of sunfish that will limit weevil populations (Creed 2000), and more research on this topic is needed. The role of invertebrate predators should also be examined (Creed 2000); however, if sunfish are limiting weevils, they will also likely limit the invertebrate predators.

Treatment sites

Successful biological control results in a suppression of the pest plant, not its elimination. Because of the potentially cyclical nature of control and the lower predictability of control temporally, biological control is most useful for long-term control in lower priority sites and over large areas where other management actions would be less feasible or cost effective. High- priority areas, where effective and rapid control is needed (e.g., boat channels, swimming beaches, docks), should be managed with other approaches. Because some of these intensive management approaches may conflict with biological control (see "Integration"), sites chosen for biological control should be areas with less disturbance and less need for immediate relief. An acceptance of partial control and a healthy native plant community in areas targeted for biological control are needed. In Houghton Lake, backwater areas or unused bays would be suitable for biological control, as would large weed beds in the center of the lake that might be unfeasible to control with other methods.

Integration

The milfoil weevil requires Eurasian watermilfoil, or its close relatives such as northern watermilfoil, to exist. Therefore, any technique that would eliminate watermilfoil from the lake would be incompatible with the use of weevils. For example, if the aim of a whole-lake herbicide treatment were to eliminate water-milfoil, it would not make sense to implement biological control during this time.

No work has been conducted on integrating milfoil weevils with chemical control. It is unlikely that registered herbicides will have any direct effect on the weevils, but elimination of the plant will eliminate the weevil host. Again, targeted chemical control for high-priority sites would be compatible with biological control at lower priority sites. It is possible that weevil augmentation or reintroduction could be used after chemical control to keep the plants

suppressed, but availability of host plants to sustain the milfoil weevil would be important. Selective chemical control leaving northern watermilfoil intact while controlling Eurasian watermilfoil would be the ideal situation, but most herbicide treatments that control Eurasian watermilfoil would likely also control northern watermilfoil. It is also possible that weevils could be used in conjunction with a slow-acting herbicide; however, this is a wholly unexplored field that requires research before implementation.

Mechanical harvesting removes the top portion of the plant where all life stages of the weevil occur. Sheldon and O'Bryan (1996a) found much lower weevil densities in harvested areas than in areas not harvested just 3 m away. Thus clearcut harvesting over large areas would be incompatible with biological control; however, harvesting strips in high-use sites and leaving adjacent unharvested plots may be an effective integrated approach (Sheldon and O'Bryan 1996a). It should also be noted that harvesting will remove meristems and place the top of the plant lower in the water column; stocking weevils into harvested plots would not be advisable due to the depth of the plant and lack of meristems.

Integration can take place both spatially and temporally. Prioritized areas for immediate relief can be separated from larger areas targeted for sustained biological suppression. If biological control is implemented in an area, at least several years must be provided to determine if suppression will take place before implementing other strategies in these plots. Following up other control methods (e.g., a whole-lake fluridone treatment) with biological control to reduce regrowth may be worthy of investigation but has not been studied.

Costs

Biological control can be quite cost effective if agents establish and develop self-sustaining populations. Because there are already weevils in Houghton Lake, costs may be limited to monitoring weevil populations and ensuring proper integration with other techniques (e.g., preventing harvesting or chemical control in designated areas). Simple monitoring of weevil populations throughout the summer could be done for several thousand dollars if students or volunteers were used. A more intensive investigation could cost $25,000 to $50,000 per year.

Introduction of weevils may not be necessary as weevils already occur in the lake and any factors that are limiting current populations would likely limit introduced or augmented populations. If there were areas where weevil densities were low or eliminated, EnviroScience provides weevils and pre- and post-stocking assessments for $1000 per 1000 weevils (Madsen et al. 2000). EnviroScience recommends stocking 3000 weevils per hectare for control within two seasons (Madsen et al. 2000). Ten 1-ha plots could be stocked and assessed for $30,000. Clearly one needs to know if some major limiting factor, such as sunfish predation, exists in the lake before using this approach.

Cost estimates for more intensive conservation strategies to enhance existing or augmented populations are not readily available. In addition to protecting

existing weevil habitat (regulation and enforcement costs), manipulations such as improving shoreline overwinter habitat or removing bluegills would be experimental and probably cost prohibitive. These approaches could be integrated with other strategies to improve overall lake health, such as a program to enhance shoreline habitat or to improve the fishery, but biocontrol would be best considered an additional benefit, not the main focus of the activity.

Lastly, an intensive lakewide augmentation could be considered. This approach would involve stocking weevils at a rate of 10 per m^2 or 100,000 per ha. This density is lower than presumed to be required for declines (>25 m^{-2}) but the weevils should reproduce and build up a population, and this density (10 per m^2) is about 13 times greater than the density recommended by EnviroScience (Madsen et al. 2000). Inundation of the entire lake would likely have success in the first year. At the current rate of $1 per weevil and approximately 4000 ha of watermilfoil, this treatment would cost $400,000,000. This is likely cost prohibitive, and rearing that many weevils would be a formidable task. More targeted approaches and integration of conservation with other control measures would be more feasible and cost effective.

Recommendations

Because milfoil weevils already exist in the lake but the extent and density of their populations are unknown, surveys are recommended to determine the extent and density of weevils throughout the lake. Ideally, these surveys would include biweekly stem surveys at numerous locations throughout the lake. Eight to ten stems (top 0.5 to 0.75 m of a plant) should be collected at each station (see Jester et al. 2000 or Newman and Biesboer 2000 for methods), and five to ten stations should be sampled in each area of the lake. The stems are returned to the lab; and weevil eggs, larvae, pupae, and adults as well as other potential control agents such as caterpillars are enumerated. Biweekly surveys from mid-May through mid-September will permit monitoring weevil generations and allow partial determination of limiting factors as well as an assessment of whether adequate densities to control the plant exist. This information can be used to develop a long-range strategy of no action, conservation, targeted augmentation, or integration with other control methods. Augmentation and conservation sites should be protected from deleterious activities (e.g., heavy boat traffic) and management activities (e.g., harvesting) that would affect the weevils and confound assessment.

It should be stressed that the effects of augmentations, conservation efforts, and effects of other control strategies on the milfoil weevil and milfoil populations should be assessed. The effects both on milfoil density and biomass and on weevil populations should be monitored. This monitoring might also suggest better integrated approaches such as the feasibility of combining biological with chemical control. Weevil monitoring, at least for the first several years, should occur more frequently than once or twice per summer. Weevil populations fluctuate from predominantly adults and eggs, to larvae, then pupae.

More frequent (e.g., biweekly) surveys allow better detection of what life stages may be limited and at what time of year.

Chemical Control Techniques

Overview and objectives

Eurasian watermilfoil has been successfully managed in the northern United States using various formulations of systemic and contact herbicides for nearly 50 years. While several formulations of both systemic and contact herbicides are registered by the U.S. Environmental Protection Agency for controlling Eurasian watermilfoil, this discussion will be limited to only those products that are currently registered in the state of Michigan and would be potentially available for use on Houghton Lake. The primary objective of this working group was to review and recommend chemical control strategies that will selectively control Eurasian watermilfoil in the lake, both on a partial- and whole-lake application scenario. Species-selective control is important, especially when treating large areas of the lake. The population of the invasive Eurasian watermilfoil can be significantly reduced while limiting negative impacts on the desirable native plant community. In addition to addressing potential milfoil control, estimates of cost of treatments, effects on nontarget vegetation, and potential environmental impacts were reviewed and presented.

To fully determine herbicide impacts on Eurasian watermilfoil and nontarget vegetation, quantitative information on the existing plant community should be gathered prior to chemical treatments. Consistently conducting quantitative plant surveys in areas treated (pre- and post-treatment) where data collected can be statistically examined will scientifically document the efficacy of the treatment and recovery of the native plant community. This information can be used when justifying the continuance or discontinuance of herbicide applications. Examples of quantitative submersed plant community surveys that can be statistically analyzed include Madsen (1999) and the ReMETRIX method.[1] Plant community assessments that were conducted on the lake in 1999 (Pullman 2000) and 2000,[1] if quantitatively measured, can provide a baseline record of the current condition of the plant community. A quantitative survey should also be conducted in succeeding years.

When submersed plants are treated, herbicide effectiveness depends upon dose and contact time (also known as concentration and exposure time relationships or CETs), which are in turn dependent upon the water exchange characteristics of the treatment zone (Getsinger and Netherland 1997). Therefore, to ensure an efficacious application of any herbicide, water exchange characteristics of the treated zone, such as seasonal retention time of the lake and/or water movement in application plots, should be investigated prior to any herbicide applications. Using this information, one can precisely predict control of the

[1] T. McNabb, Personal Communication, 17 May 2001, ReMETRIX, Carmel, IN.

target species (milfoil) and impacts on desirable native vegetation, as well as provide estimates of off-target movement of herbicide residues.

Finally, there should be an assessment of potential impacts on any threatened and/or endangered species (TES) or species of special concern (both flora and fauna) that occur in the treated areas of the lake prior to any herbicide applications. While concern for special species should be employed, it should also be noted that in many cases some TES are actually enhanced by properly timed and planned herbicide applications. When nuisance levels of an invasive plant, such as Eurasian watermilfoil, are selectively removed from a site, normal environmental conditions are restored and the rare or TES species is encouraged to utilize the improved habitat, grow, and thrive (Nelson 1999).

Contact herbicides

Overview. Contact herbicides are products that have a broad spectrum of activity and can be used to control most submersed plant species. However, a knowledge of CET relationships with respect to contact herbicides can be used to provide some degree of species selectivity. Also, the active ingredients in these products do not translocate throughout the plant, and therefore affect only the tissue that is contacted by the herbicide. With the exception of annual plants and very young perennial plants (with poorly developed rootstock or root crown tissue), contact herbicides rarely kill the entire plant. When used to control submersed vegetation, they perform well in removing or "burning down" the shoots, but do not control the rootstock or root crown tissue, which is at or below the surface of the sediment. Because of this, robust perennial species, such as Eurasian watermilfoil, that are treated with contact herbicides usually have the ability to recover from the herbicide exposure and regrow. Two contact herbicides are registered for use in Michigan that would be appropriate for controlling Eurasian watermilfoil, diquat [6,7-dihydro-dipyrido (1,2-a:2',1'-c) pyrazinediium dibromide] and endothall [7-oxabicyclo (2.2.1) heptane-2,3-dicarboxylic acid].

Diquat. Diquat is available as a liquid product (trade name, REWARD® (Table 3)) that can provide a rapid kill of submersed plant shoots, followed by a quick decomposition of the affected tissue (within 4 to 7 days post-treatment). The herbicide is usually applied from a boat directly to the stand of target vegetation by injection beneath the surface, or broadcast sprayed over the surface of the water. The application window for optimum plant control is in late spring when plants are actively growing and water temperature is above 12 °C. Extensive treatment experience in Michigan lakes has shown that one application of diquat at recommended rates can provide greater than 80 percent knockdown of Eurasian watermilfoil plants, with regrowth occurring in 6 to 8 weeks post-treatment.

Since it is a nonselective product, shoots of nontarget native plants that occur within the treated zone will also be controlled. Because diquat is readily bound to mineral clays and organic matter, this herbicide is most effective when used

Table 3
Aquatic Herbicide Manufacturers and Contact Information

Manufacturer	Address	Telephone and Fax	Web Site	Herbicide Trade Name	Active Ingredient
Applied Biochemists	W175 N11163 Stonewood Dr. Suite 234 Germantown, WI 53022	800-558-5106 phone 262-255-4268 fax	www.appliedbiochemists.com	Navigate	2,4-D BEE
Cerexagri, Inc.	630 Freedom Business Center Suite 402 King of Prussia, PA 19406	800-438-6071 phone 610-491-2801 fax	www.cerexagri.com	Aquathol K Hydrothol 191	Endothall Endothall
Griffin, LLC	2509 Rocky Ford Rd. Valdosta, GA 31601	800-242-8635 phone 912-244-5813 fax	www.griffinllc.com	Avast!	Fluridone
SePRO Corp.	115560 N Meridan St. Suite 600 Carmel, IN 46032	800-419-7779 phone 317-580-8290 fax	www.sepro.com	Sonar A.S.	Fluridone
Syngenta, Inc.	1800 Concord Pike Wilmington, DE 19850	302-476-2000 phone	www.syngenta-us.com	REWARD	Diquat

in clear water. Use of diquat in turbid water conditions will inactivate the product and result in poor or no control of treated vegetation (Hofstra, Clayton, and Getsinger 2001; Poovey and Getsinger 2002).

Rapid plant uptake, short CET requirements, and limited offsite movement of diquat make this herbicide ideal for treating small stands of plants or for use as a follow-up (spot treatment) application to remove patches of plants that might have survived a large-scale herbicide treatment. Furthermore, the activity and dissipation properties described previously also make it a good choice for conducting fairly precise treatments in and around marinas, docks, boat launches, and swimming areas. It can also be used to open up small, well-defined areas in dense stands of vegetation for boat access and/or fishing lanes. The State of Michigan imposes a 24-hour swimming restriction on the use of diquat. For complete use restrictions, refer to the current product label and contact MI-DEQ.

Currently, no CET relationships have been developed for diquat to allow for its use as a method for selectively controlling Eurasian watermilfoil. When used at rates effective for controlling milfoil, diquat will also control other native plants in the treated zone. However, the most appropriate use of diquat in Houghton Lake would be for relatively small-scale, partial-lake applications, where broad-spectrum removal of submersed aquatic plants in those settings would represent only a small proportion of the total plant community. Application of diquat in this manner would permit the integration with nonchemical techniques, such as mechanical harvesting or biocontrol insects. It was generally agreed that the cost of diquat applications would range from $500 to $560 per infested hectare treated. These costs include the current price of the herbicide and the estimated cost of application.

Endothall. Although not typically used for milfoil control in Michigan, two endothall formulations are recommended for controlling that plant, the liquid Aquathol® K and the polymer Aquathol® Super K Granule (Table 3). Recommended treatment rates range from 2 to 4 mg active ingredient (ai) L^{-1}. When endothall is used in this manner, there is a rapid kill of plant shoots that results in >80 percent knockdown within a year of treatment; however, regrowth can occur in 6 to 8 weeks. Herbicide applications should be made in spring when water temperatures are above 12 °C and plants are actively growing. The herbicide is applied by boat, and is either injected underneath the water surface into a stand of vegetation or sprayed above the surface with hand-held equipment in a broadcast application.

Research of endothall CET relationships conducted at ERDC have indicated that milfoil injury was directly proportional to the length of time plants were in contact with a given endothall concentration (Netherland, Green, and Getsinger 1991). Endothall rates that are effective for milfoil control should have at least 18- to 24-hour exposure times for best results (Netherland, Green, and Getsinger 1991). Given these exposure times, water in treatment areas should be quiescent, with minimal flow. Endothall is not affected by turbidity in the water column and can provide milfoil control in areas protected from high water exchange processes, such as coves, swimming areas, and boat docks.

Endothall is generally considered a nonselective herbicide, and recommended application rates (2 to 4 mg ai L^{-1}) may impact some native submersed vegetation. However, small-scale studies have shown that lower rates of endothall (0.5 to 1.0 mg ai L^{-1}) provide excellent control of milfoil, and significant regrowth of nontarget plants was observed just 8 weeks post-treatment (Skogerboe and Getsinger 2002). These results have yet to be verified in the field. Endothall applications in Houghton Lake would provide an opportunity to confirm these selectivity results, where low doses of endothall could be used in partial-lake treatments of 10- to 50-ha blocks. In addition, application of endothall in partial-lake treatment techniques would allow for the integration with nonchemical techniques, such as mechanical harvesting or biocontrol insects.

The State of Michigan has specific restrictions on application of the granular formulation of endothall near shore well locations; applications must be 23 m away from wells and 76.5 m away from shallow wells that are less than 9 m deep. Other water use restrictions include the following: no swimming in a treated area for 24 hours after application; 3-day restriction on taking fish from treated areas for consumption; and 14-day restriction on using treated water for irrigation, agricultural sprays, or domestic purposes. For complete use restrictions, refer to the current product label and contact MI-DEQ. The cost for application of endothall is estimated at $680-$740 per infested hectare, which includes the cost of the herbicide.

Systemic herbicides

Overview. Systemic herbicides, unlike contact herbicides, translocate throughout the plant and under ideal conditions can provide complete control of the target weed. These herbicides are absorbed primarily by the leaf and stem tissues and move to the actively growing apical regions of roots and shoots, killing the entire plant. Two systemic herbicides approved for aquatic use in Michigan for control of milfoil are the low-volatile butoxyethyl ester (BEE) of 2,4-D (2,4-dichlorophenoxyacetic acid) and fluridone (1-methyl-3-phenyl-5-[3-(trifluoromethyl)phenyl]-4(1*H*)-pyridinone). Selectivity has been reported in laboratory and field CET evaluations for both these products, in which milfoil was selectively controlled and nontarget species were unaffected or regrew after herbicide application (Getsinger, Davis, and Brinson 1982; Green and Westerdahl 1990; Netherland, Getsinger, and Turner 1993; Netherland and Getsinger 1995a, 1995b; Netherland, Getsinger, and Skogerboe 1997; Sprecher, Netherland, and Stewart 1998; Parsons et al. 2001; Getsinger et al. 2001).

2,4-D. 2,4-D BEE is a granular (clay) product (trade name Navigate® (Table 3)) that acts as an auxinlike plant hormone. Once absorbed into plant tissues, there is a moderately slow kill of shoots (7 to 14 days) and decomposition of plants (14 to 28 days), with >85 percent knockdown of mature shoots within the year of treatment. Young, actively growing milfoil plants are more susceptible to 2,4-D than are mature, slowly growing plants. In cases where milfoil is not completely killed, regrowth can occur in 8 to 12 weeks following the initial application. Control of milfoil is selective at all rates, with minimal injury to nontarget plants. However, young plants can usually be controlled with lower application rates of this herbicide. 2,4-D has been routinely used to selectively control Eurasian watermilfoil in Michigan lakes and other Midwestern water bodies for over 50 years.

The State of Michigan imposes a 24-hour swimming restriction on the use of 2,4-D and has specific restrictions on application of 2,4-D near shore well locations; applications must be 23 m away from wells and 76.5 m away from shallow wells that are less than 9 m deep. For complete use restrictions, refer to the product label and contact MI-DEQ. Partial-lake treatments using 2,4-D would include moderately sized blocks or all hectares infested with milfoil (4,000 ha). In either case, use of 2,4-D would allow for integration with nonchemical management techniques. Cost of 2,4-D application is approximately $740 per infested hectare, which includes the cost of the herbicide.

Fluridone. Fluridone (Sonar® A.S., Avast® (Table 3)) is a liquid product that is applied in the form of an aqueous suspension. Once the herbicide is absorbed by the plant leaves and stems, fluridone interrupts the carotenoid biosynthetic pathway; carotenoid pigments are necessary for plants to photosynthesize. Susceptible plants die and decompose slowly, with >90 percent knockdown in a year of treatment. If the treatment is effective, target plant regrowth usually does not occur for over 12 months. Low rates (5 to 8 μg ai L^{-1}) are selective for milfoil, with minimal injury to nontarget species. Fluridone efficacy is best provided with whole-lake treatments, or very large treatment blocks (≥50 ha).

Whole-lake treatments have been successful in water bodies ranging from 13 to 24,000 hectares (Getsinger et al. 2001). At the time of publication, state guidelines have not been developed for using granular formulations of fluridone; therefore, use of those formulations in public waters is not allowed.

The State of Michigan has special regulatory requirements for fluridone applications, whole-lake treatments in particular. At present, only spring applications are allowed with a maximum rate of 6 μg ai L^{-1} although fall application techniques at slightly higher dose rates (8 to 12 μg ai L^{-1}) are being evaluated in several Michigan lakes. The application requirements for fluridone permits to the state include results of a plant survey conducted in late summer/early fall the year prior to proposed fluridone treatment, including documentation of the Eurasian watermilfoil problem (i.e., abundance and distribution); volume calculations as the basis for the amount of fluridone requested; a 3-year vegetation management plan, including goals and 3-year treatment plan; and a product distribution plan. If a permit is granted, the permit requirements will include residue monitoring in the year of treatment and follow-up plant surveys in the year of treatment and the first and second years post- treatment. There is a 24-hour swimming restriction on the use of fluridone. For complete use restrictions of fluridone, refer to the product label and contact MI-DEQ.

Whole-lake treatments are not compatible with other control techniques in the year of treatment, but can be a prelude to integrated control methods in the years following fluridone application to keep milfoil at low levels. Large block treatments of fluridone, approximately 50 to 200 ha, are an alternative to a whole-lake treatment; however, this approach would be a new concept for state regulatory issues, such as rate of fluridone used, site and location of the treatment block, and degree of species-selective control achieved. In addition, in order to determine the rate of fluridone used in partial-lake block treatments, characterization of water exchange and dilution processes would have to be determined. Cost of fluridone applications would be in the range of $370-500 per infested hectare, which includes the cost of the herbicide.

Ecological Impacts

The modes of action of herbicides are inherently effective on photosynthetic organisms (plants), and therefore, when used according to label recommendations these compounds have no direct impacts on fish and wildlife. In many instances, using herbicides to remove or reduce nuisance levels of invasive aquatic vegetation can have many positive impacts on lake ecosystems (see Chapter 4, "Ecological Considerations"). However, using aquatic herbicides can result in some types of indirect ecological impacts on lakes, but any negative impacts are usually short term. When aquatic herbicides are used for controlling milfoil in a broad-spectrum manner, desirable native submersed plants growing in the treated area can also be removed or injured. If all submersed plants are quickly removed from an area, indirect ecological effects can occur: release of nutrients into the water column from quickly decaying vegetation (nutrients that would become available for phytoplankton and filamentous algae), removal of

structure and food sources for aquatic organisms and wildlife, and potential to roil and disrupt the sediment.

Of the herbicides available and suitable for milfoil control on Houghton Lake, diquat is the only product that would be used in a broad-spectrum fashion. However, diquat would typically be used to remove submersed vegetation and open small blocks of the lake, such as swimming areas, around docks, boat access trails, and selected shoreline areas. When diquat is used in this way, large areas of undisturbed vegetation would surround the treated areas that would dampen any sediment resuspension, act as a sink for any nutrients released into the water column, and provide adequate habitat to mitigate any reductions of such occurring in the treated areas. Since diquat is a contact herbicide, control of vegetation achieved in treated areas is temporary, as "burned-down" plants recover and resprout from unaffected rhizomes and root crowns.

The other products available for milfoil control would not be used in a broad-spectrum manner on Houghton Lake. 2,4-D is inherently selective for rapidly growing dicots (broad-leaved plants), such as milfoil, and would not injure the native submersed plants, which are primarily monocots (grasses), growing in treated areas. If applied at high rates, both endothall and fluridone can be used as broad-spectrum herbicides; however, the application rates of these products used on Houghton Lake would be low enough to provide selective control of milfoil, with little to no injury of associated native submersed plants.

Recommendations

Based on the scientific information and the documented record of chemical use for controlling milfoil, there are several viable options for using herbicides to manage milfoil in Houghton Lake. Some of these options could provide temporary (season-long) relief of nuisance levels of milfoil in selected areas of the lake, while others could provide for a more long-term (several years) alleviation to the milfoil problem. In addition, some of these herbicide options could be used in various combinations, and in integration with nonchemical methods, to extend the effectiveness of milfoil control for many years. All of these options are directly linked to the short- and long-term goals for the overall management of Houghton Lake, and as such can be prioritized only after those management goals and objectives have been developed.

The following chemical control options should be considered for managing milfoil in Houghton Lake:

a. The contact herbicide diquat can be used to reduce nuisance levels of milfoil in relatively small areas of the lake needing immediate relief, such as in nearshore areas to provide boat access to the lake, swimming areas, docks, and boat-launching areas. Although diquat is a nonselective herbicide, any injury or control of nontarget native vegetation will be restricted to the treated areas and will be short-term (seasonal). Diquat

use could also be integrated with mechanical and biocontrol techniques and selected 2,4-D treatment areas.

b. The systemic herbicide 2,4-D can be used to control milfoil in larger areas of the lake ($\geq$ 20 ha). Since this product is selective for milfoil, there will be minimal or no damage to nontarget vegetation in the treated areas and little negative impact on water quality and/or aquatic habitat. Through the judicious use of 2,4-D, milfoil can be significantly reduced in the treated areas, while the release and growth of more beneficial native submersed plants will be encouraged. Treatment strategies utilizing 2,4-D can also be developed to include integration with diquat applications, mechanical harvesting, and biocontrol techniques.

c. The systemic herbicide fluridone can be used as a whole-lake treatment of milfoil. Using low-dose application methods that have been verified in other Michigan lakes, this type of strategy can significantly reduce the milfoil throughout the lake, and allow for the recovery and growth of the native plant community, even in the year of treatment. Widespread milfoil control could be achieved for 2 to 3 years using this method. Integration of other control techniques (chemical, mechanical, and biocontrol) would not be appropriate during the year of fluridone application, but could be implemented in the year(s) following fluridone treatment, as necessary, to extend the effectiveness of the original treatment. One of the recommendations presented by the Fish and Wildlife Working Group (see Chapter 4, "Ecological Considerations") was that no fluridone treatments should be attempted on Houghton Lake. Members of this group were concerned primarily that large-scale phytoplankton blooms would occur following the fluridone applications, which would prevent recolonization of native plants and impact the fisheries. However, there is substantial empirical evidence that whole-lake fluridone treatments can provide excellent control of milfoil without causing algal blooms and without reducing native plant diversity or abundance in the year of application and beyond. Many large lakes in the northern tier of states, including Michigan, have been successfully treated in this manner. It is clear that concerns expressed by this group about whole-lake treatments will have to be addressed prior to conducting such an application.

d. The herbicide endothall can be used to selectively control milfoil in moderate-sized areas (5-10 ha). If employed, this strategy should be designed as a low-dose application and conducted as a demonstration project, to evaluate efficacy and verify results of previously conducted small-scale studies.

Other recommendations include the following:

a. Conduct an annual or semiannual quantitative vegetation survey for Houghton Lake. This information will be critical for documenting effectiveness of any treatment and recovery of the vegetation in the treated area(s) when implementing large-scale herbicide applications (or

other methods) on the lake; and the survey will probably be a prerequisite for a whole-lake herbicide treatment.

b. Conduct demonstration projects on any promising herbicides that are being developed for the control of milfoil, such as triclopyr, to determine if these products could play a role in a Houghton Lake management plan.

c. Utilize the most up-to-date information and techniques of controlling milfoil with herbicides, so that the most environmentally sound and cost-effective chemical strategies are considered prior to implementation of a treatment.

4 Ecological Considerations

Limnological Impacts of Milfoil Control Techniques

Overview and objectives

Based on an increasing body of knowledge on shallow-lake ecology, it is becoming evident that native littoral vegetation is an important component of these systems from a water quality and habitat standpoint (Grimm and Backx 1990; Ozimek, Gulati, and van Donk 1990; Smith and Barko 1990; Jeppesen et al. 1998; Scheffer 1998). Native vegetation stabilizes the sediment from resuspension and erosion (James and Barko 1990, 1994, 2000; Maceina et al. 1992) and associated nutrient recycling (Hellström 1991; Søndergaard, Kristensen, and Jeppesen 1992). They also provide habitat for invertebrates, young-of-the-year fish, and sport fishes (Miller, Beckett, and Bacon 1989; Madsen 1997 and citations therein), and a food resource for waterfowl and mammals (Madsen 1997 and citations therein).

Invasions of exotic species such as Eurasian watermilfoil can result in dramatic changes in macrophyte community structure (Figure 3), leading to changes in water quality and trophic structure. In particular, invasions of milfoil can result in suppression or displacement of native macrophyte species. For instance, invasion of this species in a region of Lake George, New York, resulted in a marked and rapid decline in the number of native species (Figure 4) (Madsen et al. 1991). Mechanisms contributing to displacement of native macrophytes by milfoil include a high photosynthetic rate and light requirement, which result in rapid canopy formation and shading of native plants (Madsen, Hartleb, and Boylen 1991). The formation of dense surface canopies by species such as Eurasian watermilfoil can lead to disruption of dissolved oxygen exchange, the development of low dissolved oxygen and/or anoxia below the canopy (Figure 5), enhanced nutrient recycling, and strong vertical gradients in pH and temperature (Honnell, Madsen, and Smart 1993; Seki, Takahashi, and Ichimura 1979). These changes may lead to physiological stress to the invertebrate and fish community, unlike conditions in a mixed native submersed macrophyte community (Madsen 1997). Fish communities may be impacted by dense, monospecific canopies of milfoil (Valley and Bremigan 2001); forage

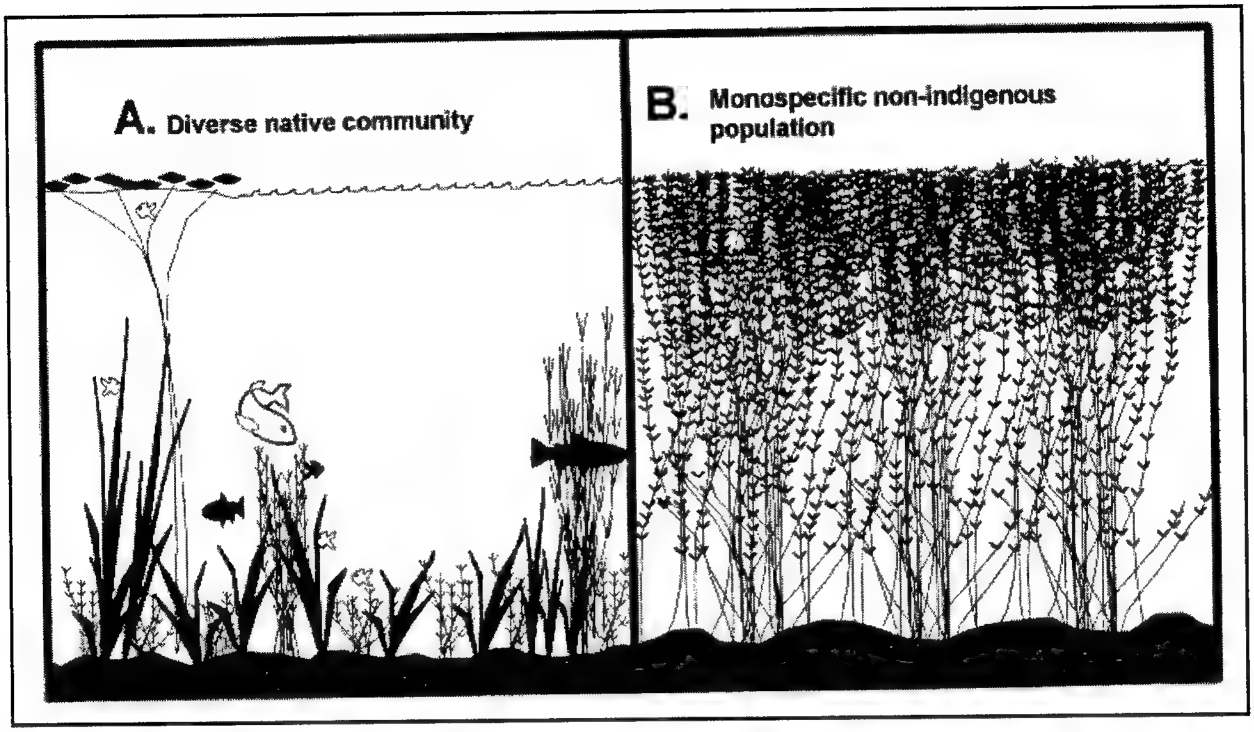

Figure 3. Conceptual schematic of a diverse native macrophyte community structure and community structure of a monospecific exotic macrophyte population such as Eurasian watermilfoil (from Madsen 1997)

species can evade predators, resulting in larger numbers of small fish at the expense of larger predatory fish (Lillie and Budd 1992). In contrast, diverse, native aquatic plant communities are often more shade tolerant than exotic species such as milfoil, with either recumbent or shorter erect stems (Madsen, Hartleb, and Boylen 1991). These communities thus exhibit architectural variety (i.e., macrophyte stems occur throughout the water column versus surface canopy formation), which can lead to vertical stability in parameters such as temperature, dissolved oxygen, pH, and nutrient concentrations.

From an ecological standpoint, control of nuisance exotic macrophytes can be considered a perturbation that often leads to temporary and/or permanent changes in the ecosystem structure and function. For instance, control of dense macrophyte stands can lead to mobilization of a relatively large nutrient pool (i.e., nutrients stored in macrophyte tissue), and subsequently may stimulate excessive algal growth. On the other hand, control of nuisance canopy-forming macrophytes can lead to improvement in dissolved oxygen conditions, which can be beneficial to other biota. Thus, there are trade-offs in water quality (both negative and positive) that must be considered when developing an aquatic macrophyte management plan. These water quality trade-offs also need to be evaluated with respect to the overall feasibility of application of a particular control technique or suite of techniques. For example, although mechanical harvesting may be less detrimental to water quality, it may not be a practical application for the given situation. Described here are specific water quality

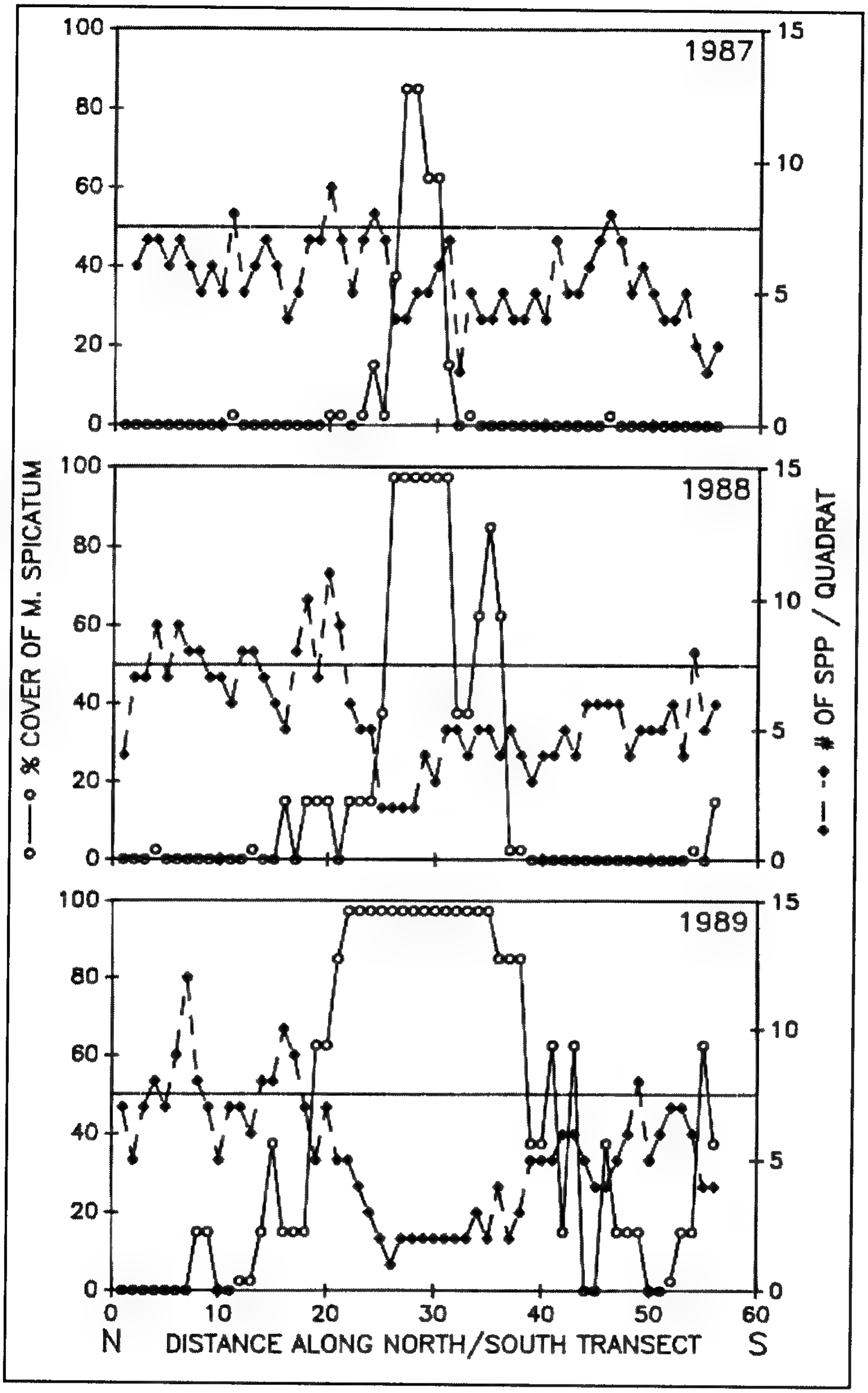

Figure 4. Changes in percent coverage of Eurasian watermilfoil and number of native macrophyte species per quadrat along a 60-m transect in Lake George, New York, between 1987 and 1989 (from Madsen et al. 1991)

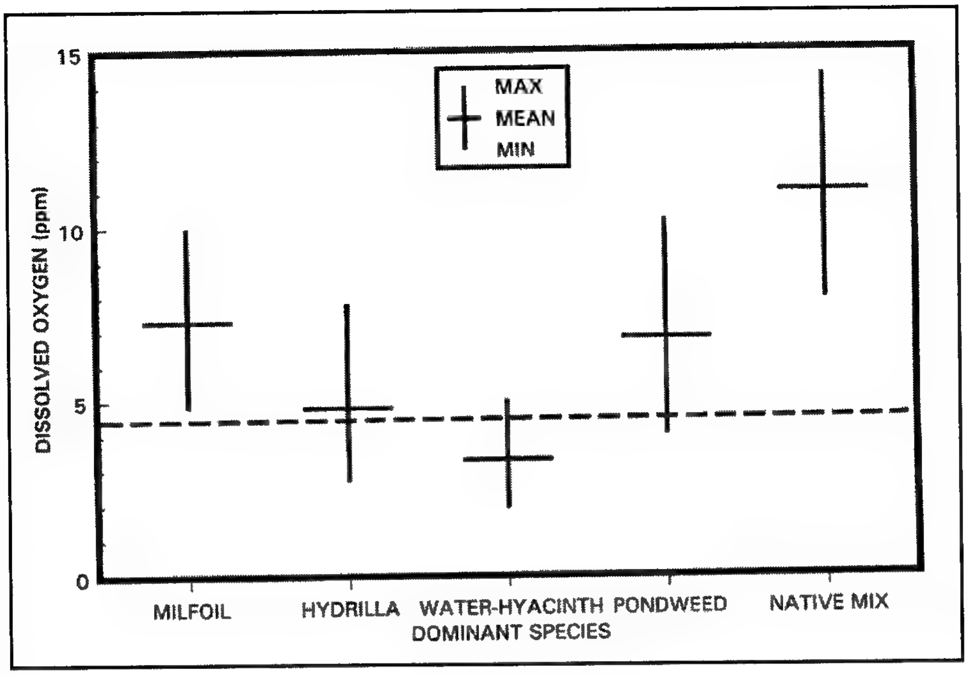

Figure 5. Maximum, minimum, and mean daily dissolved oxygen concentrations over a 48-day period in replicate ponds planted with milfoil, hydrilla, water hyacinth, floating-leaved pondweed, and a mixed native submersed plant community (from Madsen 1997)

impacts for a variety of macrophyte control techniques that are feasible for Houghton Lake. Critical information regarding milfoil density, nutrient content (may be estimated from literature values), and aerial coverage, as well as changes in native macrophyte densities, will be needed in order to make better decisions regarding impacts of control on water quality.

Macrophyte control without removal of biomass from the system

Herbicide treatment and mechanical shredding control macrophytes without removal of biomass from the system. Herbicides generally promote death through cellular damage and inhibition of metabolic functions while mechanical shredding devices clip and cut up macrophytes, leaving the tissue in the water column. Both techniques are effective in controlling extensive areas infested with nonnative plants.

Negative impacts. Aquatic macrophyte tissue can constitute a large reservoir of important nutrients such as nitrogen and phosphorus that can be mobilized directly into the water column as a result of macrophyte control and subsequent plant tissue decomposition (Table 4) (Nichols and Keeney 1973). This flux can potentially lead to stimulation of nuisance algal growth. In particular, decomposition of submersed macrophyte tissue can be rapid as a consequence of control, resulting in a pulse of nutrients to the water column. For instance, James, Barko, and Eakin (2001) demonstrated through mesh bag decomposition

Table 4
Positive and Negative Impacts of Various Macrophyte Control Techniques on Water Quality

Impacts on Water Quality	Herbicide Treatment (nonselective)	Biological Control (selective)	Mechanical Shredding (nonselective)	Harvesting (nonselective)
Potential Negative Impacts				
Macrophyte tissue decomposition and stimulation of algal growth	Y	?	Y	N
High dissolved oxygen demand	Y	?	Y	N
Enhanced sediment resuspension during treatment	N	N	Y	Y
Enhanced sediment resuspension after treatment	Y	?	Y	Y
Direct removal of invertebrates and fish	N	N	N	Y
Potential Positive Impacts				
Enhanced reoxygenation after treatment	Y	?	Y	Y
Removal of readily mobilized nutrients from the system	N	N	N	Y

experiments that direct leaching of soluble phosphorus from decomposing curlyleaf pondweed (*Potamogeton crispus*) tissue was the primary flux during the first day of senescence in Half Moon Lake, Wisconsin, resulting in the loss of nearly 40 percent of the tissue phosphorus (Figure 6). Using similar mesh bag techniques, James, Barko, and Eakin (2000) demonstrated that waterchestnut (*Trapa natans*) lost 70 percent of its initial dry mass and phosphorus and nearly 60 percent of its nitrogen content within 14 days of mechanical shredding in an experimental area of Lake Champlain, Vermont (Figure 7). Algal concentrations increased dramatically within 2 weeks in conjunction with mechanical shredding of waterchestnut (Figure 8), suggesting uptake of nutrients mobilized via plant decomposition. Since nitrogen- and phosphorus-rich sediments are the primary nutritional source for uptake and incorporation into tissue by rooted macrophytes (Barko and Smart 1986), leaving biomass in the system after control represents a recycling pathway whereby sediment nutrients are ultimately transported into the water column via plant uptake and decomposition.

Decomposition of macrophyte tissue in the system may also impart an oxygen demand due to microbiological respiratory activities during the decomposition process (Jewell 1971). In shallow wind-swept regions, dissolved oxygen demands will be offset by reaeration generated by surface water turbulence. However, in shallow embayments and other areas protected from wind-generated turbulence, dissolved oxygen demands created by macrophyte decomposition may lead to anoxia. In addition to stresses on biological components (i.e., fishes, invertebrates, etc.), the development of anoxia in bottom waters can lead to

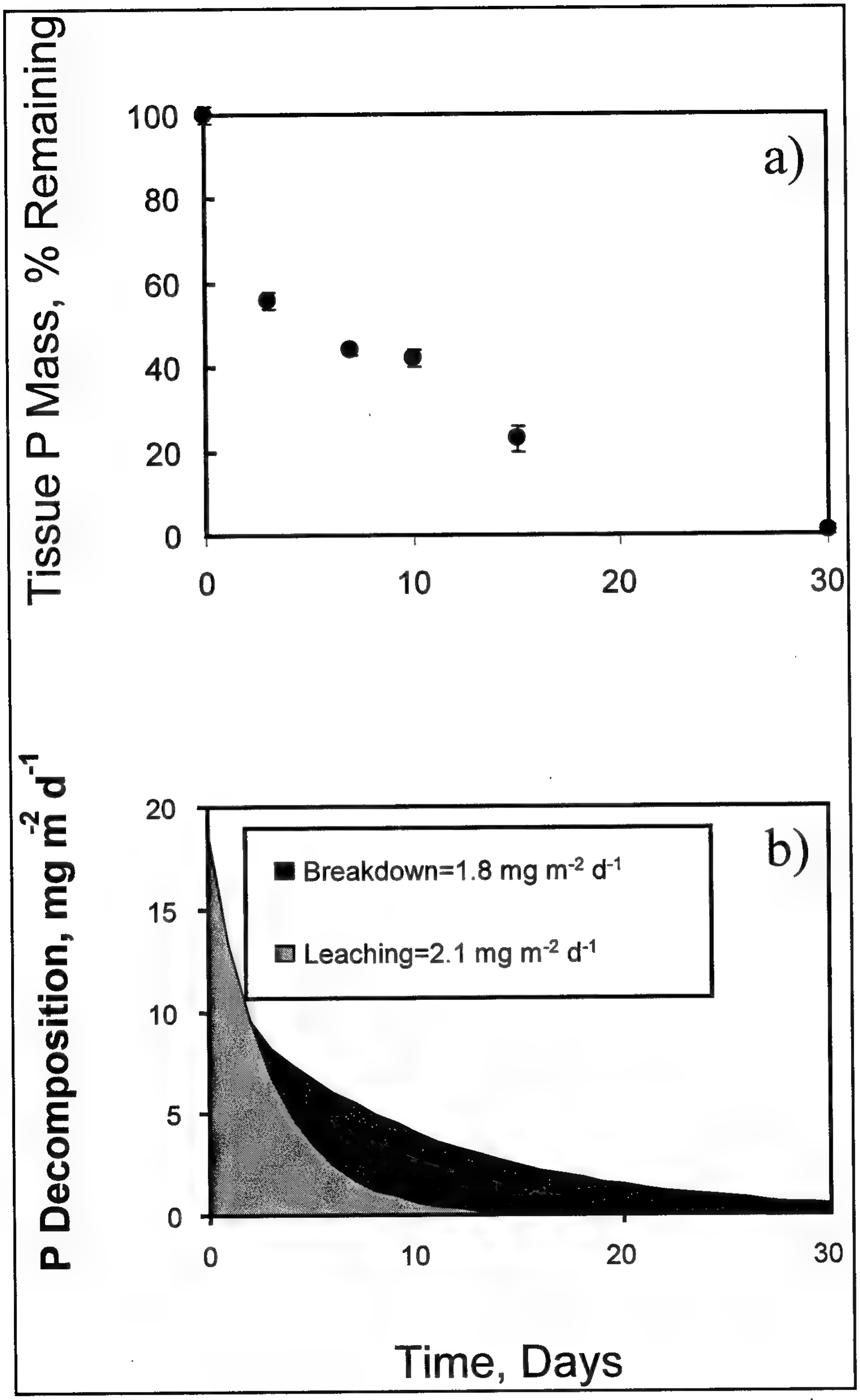

Figure 6. Curlyleaf pondweed decomposition mesh bag experiments: (a) Loss of tissue phosphorus (P) mass as a function of time and (b) variations in estimated rates of P leaching and breakdown (from James, Barko, and Eakin 2001)

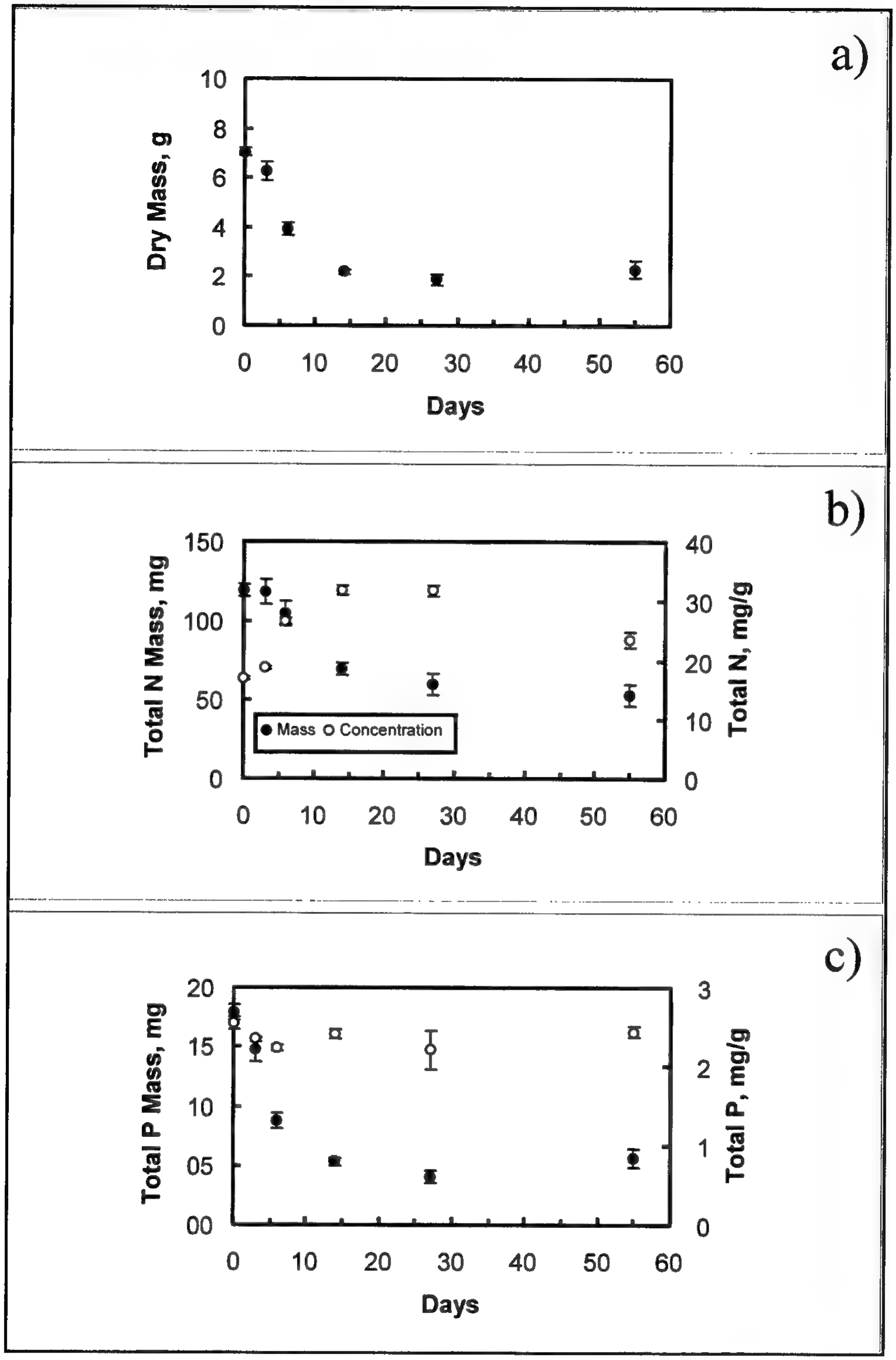

Figure 7. Waterchestnut decomposition mesh bag experiments: (a) Loss of dry mass, (b) loss of tissue nitrogen (N), (c) loss of tissue phosphorus (P) as a function of time (from James, Barko, and Eakin 2000)

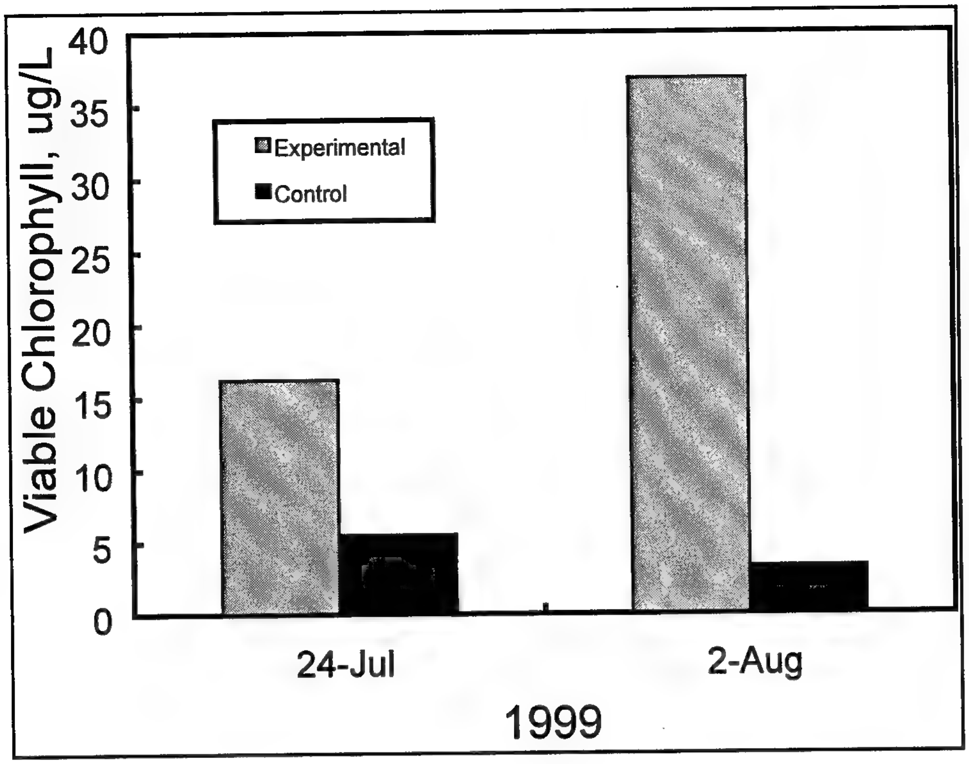

Figure 8. Changes in algal biomass (measured as viable chlorophyll) in control (i.e., no mechanical shredding) and experimental plots (i.e., water-chestnut controlled via mechanical shredding) before (24 June) and after (2 August) mechanical shredding. Plants were shredded in the experimental plot on 26 July 1999 (from James, Barko, and Eakin 2000)

enhanced nutrient flux from the sediment (Nürnberg 1984), further exacerbating the potential for stimulated algal growth. In addition, nitrification (i.e., metabolic conversion of ammonium-nitrogen to nitrate-nitrogen) ceases under anaerobic conditions, resulting in the flux of ammonium-nitrogen from the sediment into the water column for uptake by algae.

The magnitude of the impacts of plant decomposition on nutrient recycling pathways and potential stimulation of algal growth is primarily a function of the amount and type (i.e., submersed versus emergent) of macrophyte biomass that needs to be controlled in relation to physical lake characteristics such as area, volume, and flushing rate. Other considerations include the trophic state (i.e., Trophic State Index (Carlson 1977)) and the role of nutrient regulation of algal production of the lake (i.e., is the algal community phosphorus-limited?). In nutrient-poor lakes (i.e., mesotrophic and oligotrophic lakes), macrophyte decomposition and mobilization of nitrogen and phosphorus into the water column may have a greater influence on algal growth than in eutrophic (i.e., overfertilized) lakes, due to mobilization of nutrients that limit algal growth.

Half Moon Lake, Wisconsin, provides an example of the potential impacts of macrophyte decomposition on the phosphorus (P) budget of a lake (James,

Barko, and Eakin 2001). The submersed plant community in this lake is dominated by curlyleaf pondweed, a non-native plant that naturally dies back in midsummer at the peak of the algal growing season. This scenario is very similar to an herbicide treatment or a mechanical shredding of submersed macrophytes during peak biomass in the summer. In Half Moon Lake, curlyleaf pondweed biomass was very moderate at 25.4 g m^{-2} (lakewide average) near the time of dieback in June because much of the plant material had been previously removed from the system using a mechanical harvester. Yet decomposition of the remaining biomass, as measured in situ using mesh bags filled with plant material, resulted in a phosphorus flux to the water column of 1.2 mg P m^{-2} d^{-1} (averaged over a 3-month period). This flux was similar in magnitude to phosphorus flux from the sediment during the same summer period (i.e., 2.5 mg P m^{-2} d^{-1}) and represented an important source of phosphorus, overall, to the lake, contributing to excessive algal growth (80-100 mg m^{-3} chlorophyll). Eutrophication models, such as BATHTUB (Walker 1996), may be useful in predicting the potential impacts of decomposition and phosphorus mobilization resulting from macrophyte control on changes in overall algal productivity in a lake.

Control of macrophytes can also lead to some indirect negative impacts on water quality. Nonselective destruction of all macrophyte cover can result in more frequent sediment resuspension and higher turbidity in the water column (Figure 9). Particularly in shallow lakes with large fetches, such as Houghton Lake, water quality can be dominated by wind-induced sediment resuspension in the absence of submersed macrophyte coverage, promoting enhanced nutrient recycling, reduced water clarity, and higher concentrations of nuisance algae (Dillon, Evans, and Molot 1990: Maceina and Soballe 1990; Hellström 1991; Søndergaard, Kristensen, and Jeppesen 1992). In contrast, the occurrence of desirable native aquatic macrophytes in these shallow systems usually coincides with clear water and lower nuisance algal biomass (Hosper 1989; Dieter 1990; Scheffer 1990). Native macrophyte species provide refugia for zooplankton and fishes (Scheffer et al. 1993) and play an important role in stabilizing the sediment from resuspension by dampening wave activity and shear stress (James and Barko 2000).

Marsh Lake, a shallow impoundment located in western Minnesota, provides a good example of the role that native submersed macrophyte (sago pondweed, *Potamogeton pectinatus)* coverage can play in dampening sediment resuspension and improving water quality in shallow lakes. In the absence of macrophyte coverage, resuspension occurred frequently as wind speeds increased above 12 km hr^{-1} (Figure 10). During years when submersed macrophytes were present and covered the bottom of the lake, resuspension was minimal, even at very high wind velocities (Figure 10).

Positive impacts. Herbicide treatment and mechanical harvesting offer some positive impacts on water quality that need to be considered as well (Table 4). For instance, opening up the canopy of a nuisance macrophyte stand with these techniques can lead to improved habitat for benthic invertebrate and fish communities via reaeration. Dramatic changes in dissolved oxygen occurred in experimental plots after control of waterchestnut via mechanical

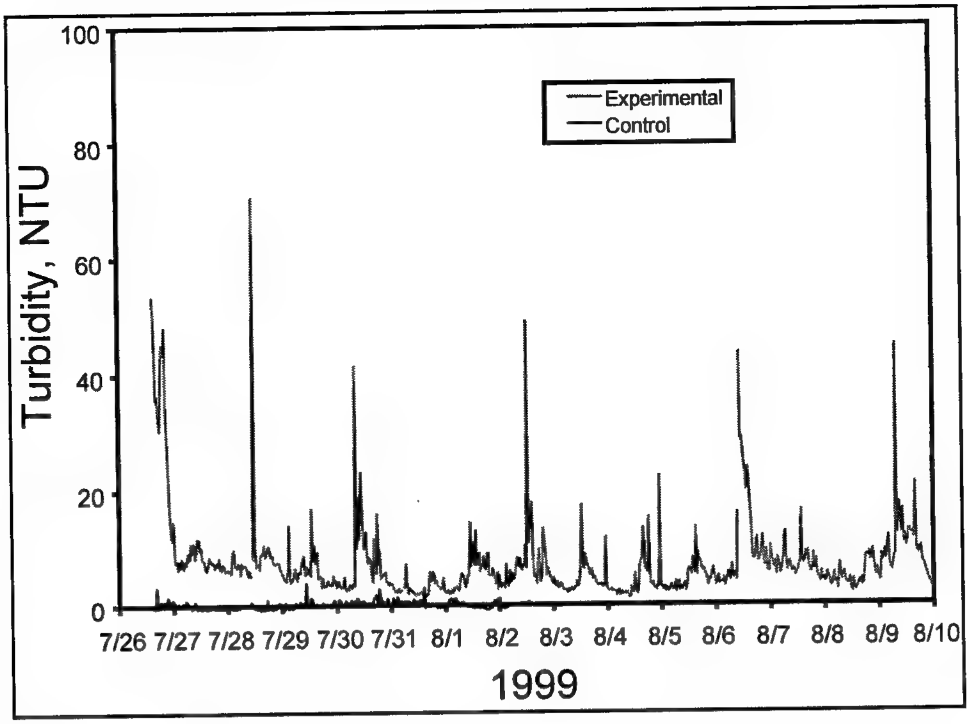

Figure 9. Variations in in situ turbidity, given in Nephelometric Turbidity Units (NTU), in control (i.e., no mechanical shredding) and experimental plots (i.e., waterchestnut, controlled via mechanical shredding) after mechanical shredding of waterchestnut at the experimental plot on 26 July 1999 (from James, Barko, and Eakin 2000)

shredding in Lake Champlain (James, Barko, and Eakin 2000). This annual non-native macrophyte forms a dense surface canopy during the summer, which inhibits reaeration from the atmosphere and promotes the development of anoxia in the bottom waters. While it was hypothesized that mechanical shredding without harvesting the macrophyte material from the system would exacerbate dissolved oxygen conditions by increasing the oxygen demand in the water column, the opposite pattern occurred (Figure 11). Dissolved oxygen increased substantially in the water column due to removal of the surface canopy and improved reaeration. The authors suggested that improved reaeration neutralized any impacts that macrophyte decomposition might have had on dissolved oxygen stores in the shredded plots.

Reaeration and increased mixing and water exchange can have an indirect positive effect on sediment-water interactions. Under oxidized conditions, the sediment microzone can act as a sink for phosphorus due to the formation of ferric hydroxides and associated adsorption of phosphorus, immobilizing it from flux to the water column. Nitrification will dominate nitrogen dynamics in the oxidized microzone as well, minimizing the buildup of ammonium-nitrogen near the bottom waters.

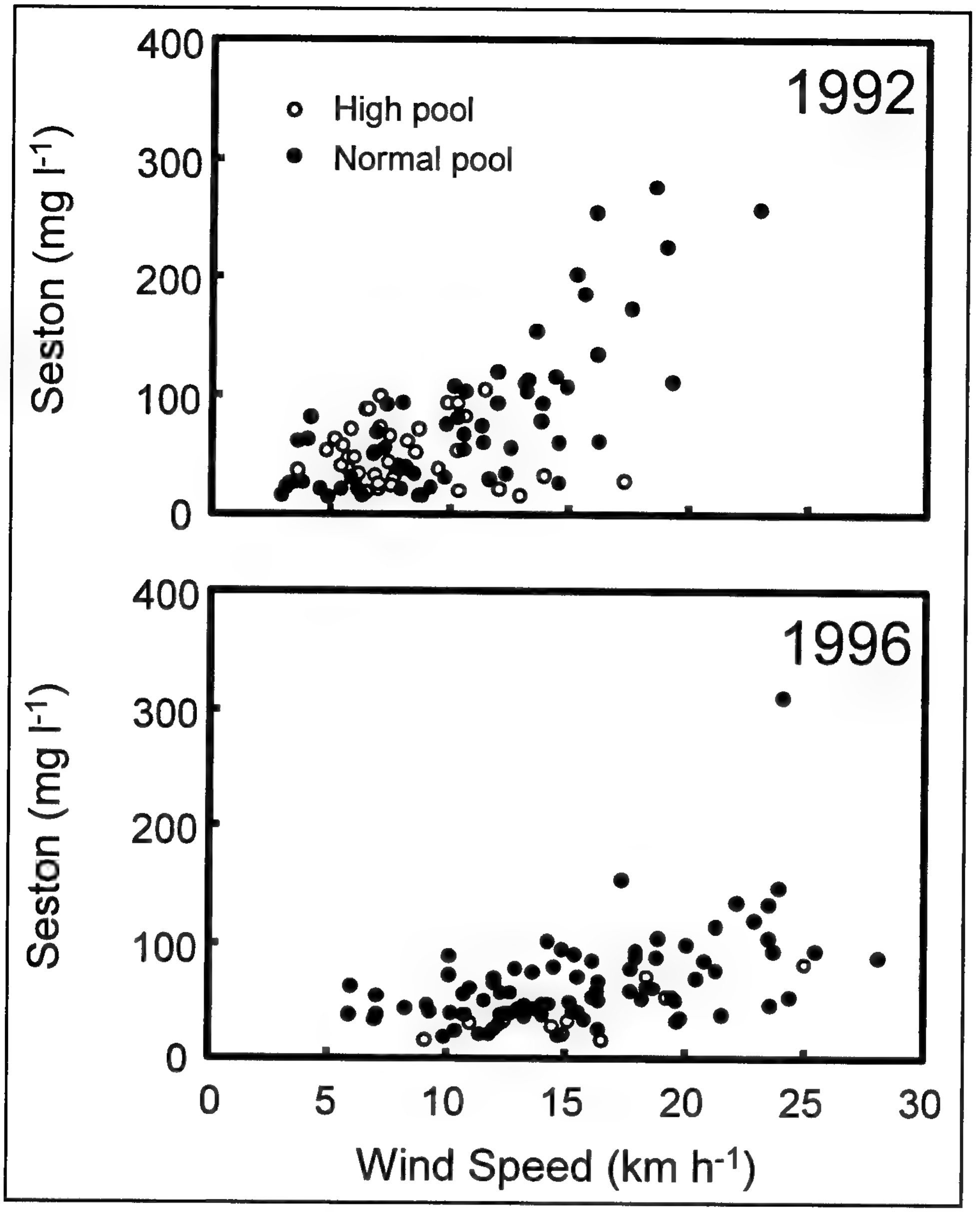

Figure 10. Relationships between wind velocity and seston (total suspended solids) in Marsh Lake during 1992 when aquatic macrophytes were absent (upper panel) and 1996 when the lake was densely vegetated with *Potamogeton* spp. (lower panel). The presence of submersed macrophytes changed dramatically the critical wind threshold required to resuspend sediment in this lake (from Barko and James 1998)

Conclusions. Nonselective control of macrophytes using methods that leave biomass in the system can lead to negative water quality impacts such as mobilization to the water column of nutrients stored in macrophyte tissue, stimulation of nuisance algal growth, dissolved oxygen demand and anoxia with associated enhancement of sediment nutrient flux, and both temporary (i.e., during the control process) and longer term (i.e., as a result of nonselective

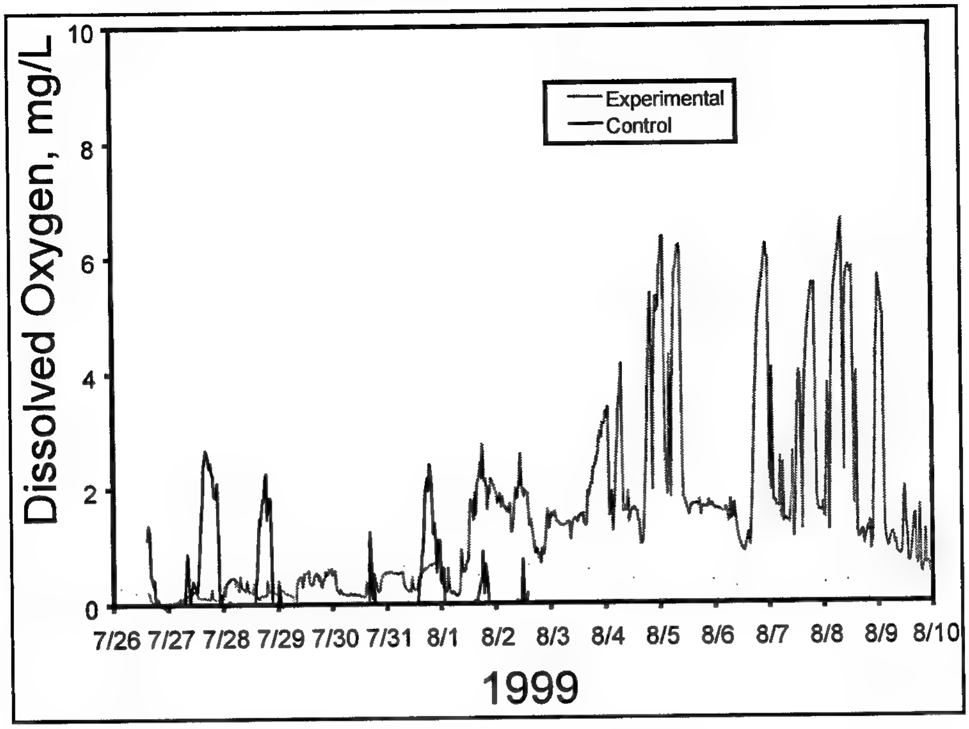

Figure 11. Variations in in situ dissolved oxygen in control (i.e., no mechanical shredding) and experimental plots (i.e., waterchestnut controlled via mechanical shredding) after mechanical shredding of waterchestnut at the experimental plot on 26 July 1999 (from James, Barko, and Eakin 2000)

destruction of macrophytes) problems with sediment resuspension and associated water quality impacts (i.e., high turbidity, nutrient recycling, stimulated algal growth). Positive impacts on water quality include opening up the canopy for reaeration and resulting shifts in redox to an oxidized sediment microzone.

If the biomass and tissue nutrient content of macrophytes to be controlled are known (this information can be obtained via a macrophyte survey), literature values on leaching and breakdown rates can be used to estimate nutrient (primarily phosphorus) flux and dissolved oxygen demand as a result of macrophyte decomposition. These overall fluxes can be incorporated into budgetary or steady-state models to estimate algal and dissolved oxygen response to macrophyte decomposition. The models must, however, be adapted to consider macrophyte (and lack thereof) influences on the light climate, as well as the nutrient budget. They must also consider periphytic uptake of nutrients and growth.

Finally, the timing and frequency of macrophyte control need to be considered in the assessment of water quality impacts. For instance, preemptive control, or control during the spring, when biomass and associated tissue nutrient mass are much lower, may lessen the severity of water quality perturbation versus control at peak biomass during midsummer to late summer. Methods that require more frequent application throughout the growing season (i.e.,

mechanical shredding every month) may exacerbate nutrient recycling versus control that persists for the entire summer period.

Macrophyte control with removal of biomass from the system

Mechanical harvesting is the primary means of both controlling macrophytes and removing biomass from the system. Generally, harvesters use conveyor belts to transport biomass to a truck that hauls it away for composting. Other harvesting techniques include hand pulling and diver-operated suction harvesting (Madsen 2000).

Negative impacts. One of the greatest impacts of mechanical harvesting on water quality is temporary resuspension of sediments during the procedure (Table 4). As with contact herbicide applications (diquat and endothall) and mechanical shredding, mechanical harvesting is nonselective; thus, removal of all of the biomass can lead to more frequent periods of sediment resuspension over longer time scales (weeks), due to increased exposure to wind and wave activity. Resuspension of nutrient-rich sediment can lead to nutrient enrichment of the water column via adsorption-desorption processes and the stimulation of algal growth. Finally, mechanical harvesting nonselectively removes and/or kills invertebrates and small fishes in the littoral zone (Madsen 2000).

Positive impacts. There are situations where removal of macrophyte biomass and associated nutrients via mechanical harvesting can be beneficial to water quality (Table 4). In these instances, the nuisance aquatic macrophyte to be controlled typically dies back in the summer (e.g., curlyleaf pondweed) as a part of its life cycle, releasing nutrients to the water column at the height of the growing season that can be utilized by algae for growth. Removing macrophyte tissue under these circumstances can reduce nutrient loading to the water column. For instance, James, Barko, and Eakin (2000) suggested that greater harvesting of curlyleaf pondweed prior to its natural senescence could significantly reduce phosphorus flux to the water column of Half Moon Lake during the summer via decomposition (Table 5). In contrast, for other macrophyte species such as milfoil, which slough bottom leaves throughout the summer and die back in the autumn (Smith and Barko 1990), mechanical harvesting during the summer will probably not be effective in reducing nutrient loads to the water column. In addition, removal of macrophyte nutrients from the system does not appear to be an effective means of reducing overall internal nutrient loads to a lake (Madsen 2000).

Like other nonselective macrophyte control techniques, mechanical harvesting may improve dissolved oxygen conditions by opening up the canopy, promoting reaeration, and reducing diel oxygen swings (Madsen 2000). This change in dissolved oxygen dynamics can lead to shifts in redox at the sediment-water interface, which can negatively affect nutrient fluxes (i.e., reduce sediment phosphorus flux out of the sediment).

Table 5
Estimated Phosphorus (P) Decomposition Rate for Curlyleaf Pondweed (*Potamogeton crispus*) as a Function of Standing Crop at the Time of Plant Senescence in Half Moon Lake, Wisconsin

Initial Standing Crop, g/m^2	P Decomposition Rate, $mg\ m^{-2}\ d^{-1}$
10	0.5
20	1.0
30	1.4
40	2.1
50	2.5

Note: Less standing crop at the time of natural dieback results in a lower overall P decomposition rate.

Conclusions. Mechanical harvesting can be associated with temporary sediment resuspension during operation. Nonselective removal of macrophyte biomass can also lead to more frequent resuspension and associated increased turbidity and enhance nutrient recycling over longer time scales. Under certain circumstances, mechanical harvesting can be beneficial in removing macrophyte tissue nutrients that would otherwise be recycled back into the water column during the height of the growing season. Opening up the surface canopy can stabilize dissolved oxygen dynamics and promote reaeration.

Biological control techniques

Very little information exists regarding the impacts of biological control of macrophytes on water quality. However, many of the changes in water quality described previously are probably applicable to this control technique as well (Table 4). Successful biological control will result in a change in the density or elimination of the target species. In the case of milfoil, biological control will likely open up the canopy allowing for greater light penetration in the water column for native macrophyte growth. Since biological control is less abrupt than other control measures (i.e., the macrophytes are not destroyed in a relatively short time frame), recycling and mobilization of nutrients into the water column will likely not be as dramatic as for herbicide treatment and mechanical shredding. If algal growth is limited by the availability of phosphorus, due to slower decomposition as a result of the control technique, changes in macrophyte community architecture (i.e., canopy- versus meadow-forming communities) and, thus, increased light penetration, will not necessarily be followed by an increase in algal growth. Because biological control is selective, sediments will be stabilized from resuspension by native macrophytes that are not impacted by the control agent. Finally, diel variations in variables such as dissolved oxygen and pH will likely become dampened as a result of

elimination of the nuisance macrophyte species, creating more favorable habitat for invertebrates and fish.

Watershed-lake management considerations and macrophyte control

Watershed influences on lake water quality and macrophyte growth need to be considered within the context of macrophyte control. While milfoil is an exotic, invasive species that spreads to lakes primarily via inoculation, there are watershed-related factors that may promote the persistence of this species in a lake. As riparian development around the lake increases, the likelihood of increased sediment and nutrient inputs to the lake increase as well, which may exacerbate milfoil presence. Increased sedimentation and storage of watershed-derived nutrients in the sediment can promote milfoil growth and persistence at the expense of native species. Since it is an opportunistic invader, it can flourish in nutrient-rich, fine-textured sediment and quickly form a canopy, particularly in turbid water, shading out native species. Dense stands of macrophytes like milfoil can, in turn, further promote accretion of incoming sediment loads, providing a mechanism for increasing sediment surface area that can be colonized by macrophytes in a lake (Carpenter 1981; James and Barko 1990). Thus, reducing sediment loading, or its accretion, should be a secondary goal of aquatic plant management.

Another watershed consideration in aquatic macrophyte management is the role that accelerated eutrophication may play in exacerbating the growth of nuisance algae. Increased watershed nutrient loading (primarily phosphorus) in conjunction with riparian development may promote the occurrence of blue-green algae blooms in association with changes in macrophyte community architecture (i.e., reduction in canopy-forming biomass). Surface algal blooms can also have an impact on light penetration, thereby influencing the growth of native macrophyte species. Thus, one problem is being replaced by another one due to accelerated eutrophication in conjunction with nuisance macrophyte control.

It is recommended that a water quality monitoring program be implemented in conjunction with an aquatic macrophyte control plan. The goal of the water quality monitoring program should be to document, over long time scales, changes (if any) in water quality that might be symptomatic of accelerated eutrophication. The program should consider budgetary analysis (i.e., how much is going into the lake, how much is leaving the lake, how much is being stored in the lake) of hydrology, sediments, and nutrients (primarily nitrogen and phosphorus). Major tributary inflows and the discharge should be monitored for flow and water quality to determine loading, discharge, and retention of sediment and nutrients in the lake over an annual cycle. In-lake stations should be monitored at monthly intervals during the ice-free period for variables such as temperature, dissolved oxygen, pH, secchi disk transparency, chlorophyll, and total nitrogen and phosphorus. Data can be compiled in the form of an annual data summary so that year-to-year variations and long-term trends can be

evaluated. Sound decisions regarding watershed rehabilitation to improve water quality and promote native macrophyte community persistence can then be made.

Fish and Wildlife Considerations and Milfoil Control Techniques

Overview and objectives

Houghton Lake has in the past and currently contains valuable fish and wildlife resources that are important not only to consumptive users, but also to the ecological integrity of the lake and surrounding area. All types of aquatic vegetation including submersed, emergent, and floating-leaved are significant components of all lake ecosystems and are critical to support successful reproduction and recruitment, and provide food resources, either directly or indirectly, for growth for a wide variety of aquatic animals.

Aquatic plant management plans should focus on maintaining natural habitats and attempting to reestablish native aquatic vegetation. Native submersed aquatic plants provide an important component to lake systems that enhance fish and wildlife resources (Engel 1990). However, in the absence of native submersed vegetation, an exotic aquatic plant, such as Eurasian watermilfoil, can furnish habitat to fish and other aquatic animals and provide benefits to the ecosystem (Engel 1995). Yet fundamental questions about Eurasian watermilfoil-fish and wildlife interactions remain: (a) can this invasive species provide quality fish and wildlife habitat (as do native plants); and (b) at what levels of growth and abundance do negative impacts of this plant outweigh any potential positive attributes?

Houghton Lake contains a diverse sport fishery comprising primarily bluegill, pumpkinseed (*Lepomis gibbosus*), rock bass (*Ambloplites rupestris*), black crappie, largemouth bass (*Micropterus salmoides*), smallmouth bass (*Micropterus dolomieui*), walleye (*Stizostedion vitreum*), and yellow perch . In the past, northern pike (*Esox lucius*) were common, but have declined substantially over the past 10 to 20 years due primarily to the loss of wetlands and extensive beds of shoreline emergent vegetation and midlake wild rice beds that provided a substrate for egg adherence and successful reproduction. About 50 species of fish can be found in Houghton Lake, and biologists consider the prey base good for predator fish. Although no fisheries survey data are available, the professional opinion of biologists with the MI-DNR suggests that the fishery is excellent. Even with the expansion of Eurasian watermilfoil, no adverse impacts on the fishery have been observed yet. The most recent available report (Schrouder 1993) states that from 1962 to 1993, no major changes have occurred in the sport fishery and the fish community appears to be fairly stable. However, Schrouder (1993) infers that there is some concern about recent declining sport fish catches. In 1959, about 1,000,000 hours effort^{-1} year^{-1} (124 hour^{-1} hectare^{-1}year) of fishing were exerted on the lake, which is high for a

public water body. More than likely, fishing effort has increased during the past 40 years.

Houghton Lake serves as an important migration stop for waterfowl, particularly diving ducks. Aerial fall surveys conducted by the MI-DNR have shown variable waterfowl use on the lake, but no precise temporal trends have been determined (Figure 12). When wild rice beds were present on Houghton Lake, the lake was quite heavily used by waterfowl hunters. With the loss of these beds, waterfowl hunting has declined dramatically.[1] Houghton Lake is also an important resource for ospreys and eagles; at least 27 pairs of ospreys and 7 pairs of eagles rely on the lake for feeding sites for fledglings.[1] The lake is also believed to be an important foraging site for migrant and nonbreeding eagles, ospreys, loons, black terns, and other waterbirds.

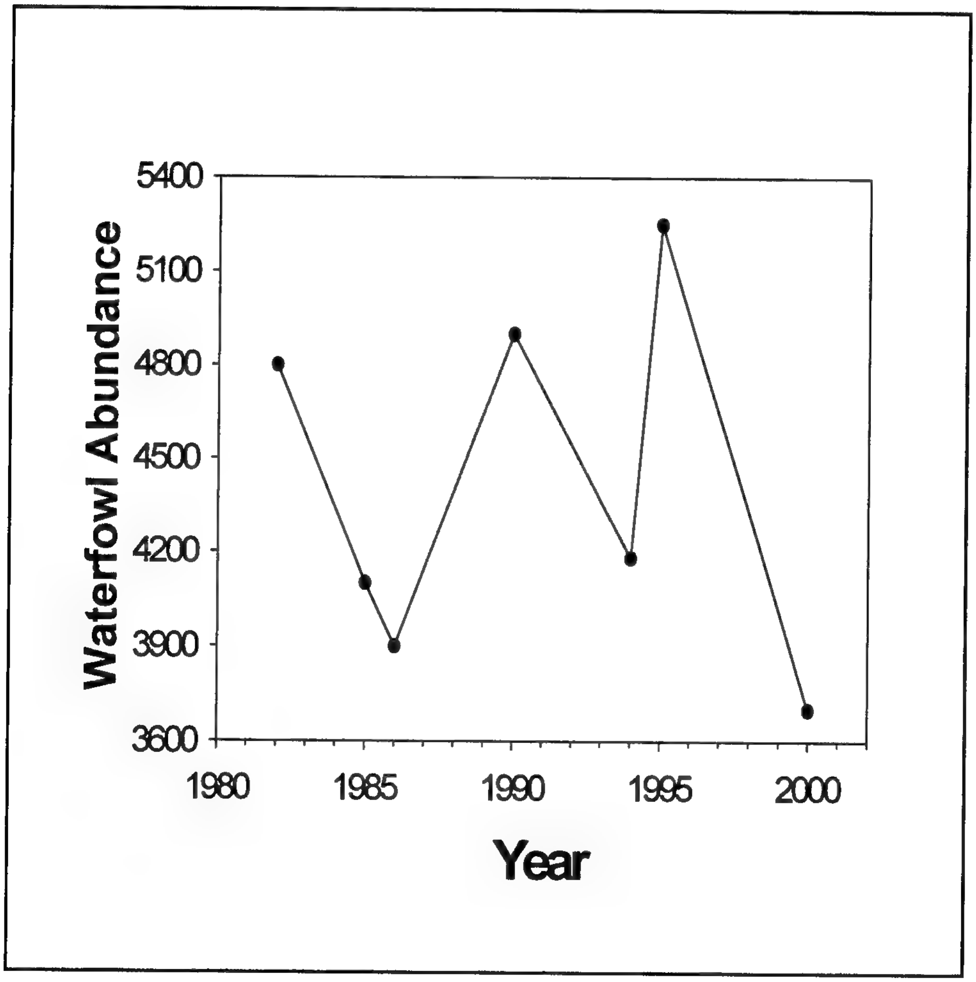

Figure 12. Areal waterfowl counts from Houghton Lake taken in early November

[1] D. Pavlovich, Personal Communication, 2 July 2001, Michigan Department of Natural Resources, Houghton Lake, MI.

While the fish and wildlife management community of Michigan generally recognizes the need to limit the impacts related to the invasive species Eurasian watermilfoil, much concern and debate still surround the type and level of control techniques available for managing this plant in such important natural resource assets as Houghton Lake. The primary objectives of this working group were to review viable Eurasian watermilfoil control techniques, appropriate and legal for Michigan waters, and to point out potential benefits and risks associated with the use of those techniques when applied to Houghton Lake. Since there were some irreconcilable differences in the opinions and recommendations of various members of the Fish and Wildlife working group, the following section provides the general consensus of the group. In addition, the suggestions and recommendations of the group leader, Dr. Mike Maceina, are included in the next section.

Consensus on aquatic plant management

Whole-lake control of Eurasian watermilfoil is not acceptable and should not be attempted. Caution should be exercised when attempting to control this plant. If whole-lake removal of Eurasian watermilfoil is achieved, a risk exists to cause turbidity to increase via resuspension, thereby creating a phytoplankton bloom. If water clarity is poor, the goal of reestablishing native submersed vegetation cannot be realized. Although Eurasian watermilfoil is not desired or preferred, this plant helps to maintain water quality and water clarity and provides fish and wildlife habitat. A massive phytoplankton bloom has the potential to negatively affect the valuable fish and wildlife resources found on Houghton Lake. A priority should be to restore Houghton Lake to its previous condition, including reestablishment of native submersed aquatic plants, shoreline emergent plants, and wild rice in areas that historically contained these plants.

Specific management goals. The group recommends the following goals:

a. The group feels that the primary aquatic plant problem and conflict on Houghton Lake is windrowed Eurasian watermilfoil that impacts shoreline property. Instead of large-scale herbicide applications to control this plant, a program needs to be planned, funded, and initiated that will mechanically remove windrowed Eurasian watermilfoil from private and public shoreline areas.

b. Total plant coverage (including submersed and emergent species) should be maintained at about 50 percent areal coverage or about 4,000 ha. Although data are limited, according to a survey conducted in 1973 when Eurasian watermilfoil was not found in Houghton Lake, less than 50 percent of the areal surface contained emergent and submersed plants in well-defined zones (Evenson and Hopkins 1973). Historically (pre-1950s), Houghton Lake likely contained 50 to 80 percent coverage of

rooted aquatic macrophytes, but a reduction in plants occurred after installation of a lake-level control structure.[1]

c. Replace Eurasian watermilfoil with native submersed vegetation using a variety of techniques including mechanical, chemical, and biological control methods. This action will promote greater plant diversity, and will benefit invertebrates, fish, and waterfowl as well.

d. Wild rice communities need to be restored in midlake areas. If substantial areas of wild rice can be established, then this may hinder windrowing of Eurasian watermilfoil along the shoreline. This plant will also provide needed habitat necessary for successful northern pike spawning.[1] Two artificial marshes were constructed in the 1960s and have failed to provide adequate spawning and nursery areas to northern pike (Schrouder 1993). Operation of these marshes to increase the northern pike population was discontinued in 1978 (Schrouder 1993). In addition, wild rice communities will attract and maintain waterfowl populations.

e. An effort needs to be made to restore natural shoreline areas by removing seawalls (bulkheads) and replacing these structures with native emergent vegetation and riprap. This will enhance the littoral shoreline community for all types of animals by providing improved habitat (Jennings et al. 1999; Radomski and Goeman 2001). The dam controlling water levels in Houghton Lake on the Muskegon River water prevents fish migration (O'Neal 1997).

Recommendations. The group recommends the following actions:

a. Water levels should be restored to natural levels. Maintenance of artificially high water levels has caused the need to construct seawalls (bulkheads) and severely reduced native shoreline emergent plant communities. At present, legally established lake levels need to be strictly maintained at 346.9 m referred to mean sea level and preferably lower than this. At all times, exceeding water levels should be prevented and during spring (May to June), water levels should be decreased about 0.5 m below the legal lake level to promote the growth of wild rice. Typically in April each year, water levels have been increased about 0.5 m above the legal lake level, these high levels are maintained through the summer, then typically lake levels are reduced in the fall.

b. No fluridone treatments should be attempted in Houghton Lake. Large-scale fluridone treatments incur the risk of mass removal of Eurasian watermilfoil, which increases the potential for noxious phytoplankton blooms, increasing turbidity and resulting in the secondary removal of a

[1] R. O'Neal, Personal Communication, 2 July 2001, Michigan Department of Natural Resources, Twin Lake, MI.

significant portion of the submersed macrophyte community that supports fish and wildlife. Because of regulatory issues in Michigan and the large size of this lake, partial-lake utilization of fluridone would not be possible because of questions as to the maximum allowable concentration in the water that would provide selective control of milfoil.

c. Conduct small (5- to 50-ha) test plots using the aquatic herbicides 2,4-D, diquat, and/or endothall to attempt to control Eurasian watermilfoil and promote native plants. Funding should be obtained to monitor changes in plant communities closely.

d. Intensively stock the Eurasian watermilfoil weevil and address the potential overwinter problems related to homeowner pesticide and land use. Funding should be obtained to monitor weevil populations and damage to the target plant.

e. Mechanical harvesters should be used to provide boat lanes near boat launches.

f. Start an aggressive public education campaign supported through the HLIB to encourage lake-front home owners to remove seawalls.

g. Other biocontrol options such as fungus and pathogens should be explored.

h. Through the HLIB, establish an advisory committee to assist in recommending and coordinating aquatic plant management activities on the lake. This board should be composed of a couple of technical aquatic plant management experts, citizens that represent different interest groups on the lake (i.e., power boating/skiing, fishing, hunting, aesthetics), a couple of members from the MI-DNR to provide input for maintaining and improving fish and wildlife resources, and a representative from the source that will provide the funding for aquatic plant management activities.

Comments and recommendations by Dr. Michael Maceina, Working Group Leader

Below are additional comments and recommendations that do not necessarily represent the viewpoints or opinions of other members of the Fish and Wildlife working group; however, I believe that these viewpoints should be included in this discussion of managing Houghton Lake. During the past 20 years, I have been involved with research to seek best technical solutions to aquatic plant issues that often contain conflicting interests and needs among diverse user groups. I have worked extensively on this topic in the southeastern USA via Auburn University, and I have conducted aquatic plant-fishery contract research for the Georgia Department of Natural Resources, U.S. Army Corps of Engineers, Tennessee Valley Authority, and the Florida Department of Environmental Protection. I have also served as a consultant for a number of fish

conservation agencies and other groups to provide input to aquatic plant management decision making. Finally, I have published about 40 peer-reviewed scientific papers that examined interactions among aquatic plants, fish, and water quality with management implications.

a. I agree with the working group on fish and wildlife considerations that a whole-lake application of fluridone not be conducted. I feel the risk for an irreversible phytoplankton bloom that will prevent recolonization of native submersed macrophytes is minimal, but does exist. In larger lakes, the predicted effects of such a large-scale manipulation are less precise than in smaller water bodies. Instead, I support smaller fluridone treatment application plots (100 to 200 ha) realizing a variance would need to be granted to increase concentrations above 6 μg ai L^{-1}. I recommend experts in herbicide technology explore this option with appropriate research to determine feasibility. I support the working group's recommendations to use other approved aquatic herbicides such as diquat and endothall to control Eurasian watermilfoil.

b. I suggest that either the MI-DNR Fisheries Division or a contract be developed with another institution (for example in-state university fishery programs or private firms) to examine in detail fish-aquatic plant relations in Houghton Lake. I was extremely surprised to find that very little fishery data exist for a lake of this size, which is generally considered a major natural resource in the region. Both creel survey and fish data need to be collected with fish population assessments made in both vegetative and unvegetated areas of the lake. A commitment to long-term monitoring/research should be implemented because I feel that aquatic plant management activities will likely occur on this lake over a long period of time. I perceived from the May 16-18 meeting that currently the fishery and fish population is in "good shape" as Eurasian watermilfoil has covered nearly 50 percent of the lake's surface during 1999 and 2000. However, I heard historically that the fishery and fish population has been in "good shape" since the late 1950s when that plant was not present and native macrophyte abundance may have been lower. Because of limited data, I question the group's recommendation that Houghton Lake needs 50 percent coverage of all macrophytes to maintain a quality sport fishery and a healthy and diverse fish population.

c. I recommend that empirical relationships be developed between plant abundance and fish throughout Michigan, with considerations made to water quality, lake morphometrics, and hydrology. This knowledge is lacking for north temperate glacial lakes. I have found in larger southeastern U.S. lakes and reservoirs that contain warmwater fish, that 10 to 40 percent areal coverage of macrophytes increases the probability of supporting more ideal sport fisheries and provides ecological stability to these systems. Higher levels of submersed macrophytes have the potential to adversely impact not only fishery resources, but other biota. This optimum 10 to 40 percent range for areal coverage of plants may not be accurate or suitable for Michigan lakes, and therefore, the need to

examine this to assist in aquatic plant management decision-making process is paramount. Eurasian watermilfoil has the potential to continue to spread and pose problems in other Michigan lakes. More than likely, Eurasian watermilfoil will never be eliminated from Houghton Lake although abundance will vary greatly over time due to management and natural fluctuations.

d. As a follow-up to points *b* and *c*, aquatic plant managers and fishery biologists need to coordinate their respective activities to collect accurate data to assist in the decision-making process (statewide). When potential aquatic plant conflicts appear to be emerging, resource managers should be proactive and not reactive. I feel the restoration of Houghton Lake to a more natural state with extensive shoreline vegetation, large marshes or stands of midlake emergent vegetation for northern pike spawning, lower lake levels, reestablishment of wild rice, and the removal of seawalls would be a worthy endeavor and should be explored. However, socially and politically some or all of these initiatives will be difficult to achieve or likely never occur. These represent different philosophical beliefs between myself and the working group. Being involved with these issues for a number of years, I realistically support aquatic plant management activities that protect and optimize fish-wildlife benefits, but that are also socially and politically achievable.

e. Lake managers including plant and fishery personnel need to interact with stakeholders to listen, communicate, provide tradeoff analyses, and attempt to manage plants that optimize all the resources that a lake offers. Michigan appears to have an excellent infrastructure to facilitate such exchanges through local lake citizen associations and lake improvement boards.

5 Development of a Management Plan

Based on a review of the historical data on the ecological status of Houghton Lake and the documented negative impacts that Eurasian watermilfoil can have on northern lake ecosystems, it is clear that this milfoil infestation can cause problems for the overall health of the water body. These problems include consequences to biological diversity, important fish and wildlife resources, recreational activities, and economics in the region. Since milfoil currently occupies such a large percentage of the system, it is not realistic to believe that the plant can be eradicated from Houghton Lake. However, it is possible that actions can be undertaken to greatly reduce the amount of milfoil in the system and keep milfoil populations at a reasonably low level, while restoring and conserving the recognized benefits of a diverse native aquatic plant community.

In order to achieve such a goal, it is imperative that a lake management plan be developed to address the short-term problems associated with the infestation for the next 1 to 3 years, followed by addressing the long-term reduction and continued control of milfoil in Houghton Lake over the next several decades. At a minimum, this plan should rely upon the following items and issues:

a. Prioritization of the most valuable resources and critical uses of the lake is needed to design and implement activities for restoring and maintaining Houghton Lake in a healthy condition. This process should forecast resources and uses over the next 5, 10, and 25 years.

b. Proven techniques for controlling milfoil in an environmentally sound manner, including biological, chemical, and mechanical, and the potential integration of any or all of these techniques must be carefully reviewed and assessed. Particular attention should be given to the selective nature of the method(s) employed (i.e., minimizing damage to nontarget vegetation in space and time), extent of ecological impacts, and the effort and costs involved in implementation of selected milfoil control methods.

c. Watershed management practices, including maintenance of shoreline property and lake level issues, should be reviewed and assessed to

determine impacts of those processes on the implementation and success of milfoil control techniques applied to the lake.

The specific guidance for viable milfoil control options provided in this report will be useful for developing the management plan. In addition, critical input should be obtained from the HLIB, the MI-DEQ and MI-DNR, the Michigan State Extension Service, and the Detroit District. Finally, input from other stakeholders such as the Houghton Lake Lake Association, local townships, recreation and lake user groups, and interested members of the general public should be solicited.

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Appendix A
List of Workshop Participants

Eric Bacon
MI-DEQ
PO Box 30458
Lansing, MI 48909-7958
517 241 9007
baconer@michigan.gov

John Barko
CEERD-EV-E
3909 Halls Ferry Rd
Vicksburg, MS 39180
601 634 2498
barkoj@wes.army.mil

Harland Boik
HLIB
1341 E Houghton Lake Dr
Houghton Lake, MI 48629
989 366 3654
HRDBK@voyager.net

Pearl Bonnell
MI Lake & Stream Assoc
PO Box 303
Long Lake, MI 48743-0303
989 257 3583
pbonnell@mslwa.org

Sheridan Cole
HLIB
5608 Butler Rd
St. Helen, MI 48656
989 389 7174

Bob Gardolfi
HLIB
200 Clearview Dr
Houghton Lake, MI 48629
989 422 5922

Carl Geiger
HLIB
2986 Teed Rd
Houghton Lake, MI 48629
989 422 5922

Kurt Getsinger
CEERD-EP-P
3909 Halls Ferry Rd
Vicksburg, MS 39180
601 634 2498
getsink@wes.army.mil

Mike Grodowitz
CEERD-EE-A
3909 Halls Ferry Rd
Vicksburg, MS 39180
601 634 2498
grodowm@wes.army.mil

Don House
HLIB
116 Laurel Lane
Houghton Lake, MI 48629
989 422 5776
donho@i2k.com

Bill James
CEERD-Eau Galle Lab
Resource Managers Office
Spring Valley, WI 54767
715 778 5896
jamesw@wes.army.mil

Jerry Kilburn
Lake Township
11675 W Shore Dr
Houghton Lake, MI 48629
989 422 5446

Diana Klemans
MI-DEQ
PO Box 30458
Lansing, MI 48909-7958
517 373 8001
klemansd@michigan.gov

Mike Maceina
Dept. Fisheries and Allied Aquacultures
204 Swingle Hall
Auburn University
Auburn, AL 36849
334 844 9319
mmaceina@aceag.auburn.edu

John Madsen
Biological Sciences
S-242 Trafton Science Center
Minnesota State University
Mankato, MN 56001
507 389 5728
john.madsen@mnsu.edu

Terry McNabb
AquaTechnex
2900 29th Ave, SW, Ste E-1
Olympia, WA 98512
360 754 3460
terry@aquatechnex.com

Scott McNaught
Department of Biology
Central Michigan University
Mt. Pleasant, MI 48859
517 774 1335
mcnau1as@cmich.edu

Lyman Bud Miller
Houghton Lake Lake Association
410 Old Trail Dr
Houghton Lake, MI 48629
989 366 9712

Ray Newman
Dept Fisheries and Wildlife
1980 Folwell Ave
St. Paul, MN 55108-6124
612 625 5704
RMN@fw.umn.edu

Rich O'Neal
Michigan DNR-Fisheries Division
Muskegon State Game Area
7550 E Messenger Rd
Twin Lake, MI 49457
231 788 6798
onealr@michigan.gov

Roman Pacella
HLIB
326 Beverly Dr
Prudenville, MI 48651
989 366 5684
rpdcotom@voyager.net

Dick Pastula
HLIB
8426 W. Houghton Lake Dr
Houghton Lake, MI 48629
989 422 5915
pastula@iserv.net

Doug Pavlovich
Michigan DNR-Wildlife Division
180 S. Harrison Rd
Houghton Lake, MI 48629
989 422 5192
pavlovid@michigan.gov

Angela Poovey
CEERD-EP-P
3909 Halls Ferry Rd
Vicksburg, MS 39180
601 634 2498
pooveya@wes.army.mil

Doug Pullman
Aquest Corporation
5212 Bernada Dr
Flint, MI 48506
810 736 5251
dpull24338@aol.com

Tom Rozich
Michigan DNR-Fisheries Division
8015 Mackinaw Trail
Cadillac, MI 49601
231 775 9727 x6070
rozicht@michigan.gov

Jay Sandow
HLIB
2365 Long Point Dr
Houghton Lake, MI 48629
989 422 5059
mjsandow@iserv.net

Craig Smith
Environmental Consultant
1640 Bliss St
Haslett, MI 48840
616 293 9754

Tom Smith
Office of US Representative Mike Camp
7190 W. Houghton Lake Drive (M-55), Suite 106
Houghton Lake, MI 48629
517 631 2552
thomassmith@mailhouse.gov

Roy Spangler
Michigan State University-Extension
PO Box 507
Roscommon, MI 48653
989 275 5043

Mike Stewart
CEERD-EE-A
3909 Halls Ferry Rd
Vicksburg, MS 39180
601 634 2498
stewarr@wes.army.mil

Jim Turner
Office of US Senator Carl Levin
1810 Michigan National Tower
124 W. Allegan
Lansing, MI 48933
517 377 1508

Charlie Uhlarik
USACE Detroit District
477 Michigan Ave
Detroit, MI 48226
313 266 6753
Charles.A.Uhlarik@lre02.usace.army.mil

Ray Valley
US Forest Service
PO Box 982
Walker, MN 56484
218 547 4823
rdvalley@fs.fed.us

Charles Van Duser
HLIB
105 Island Dr
Houghton Lake, MI 48629
989 422 2010

Rick Vosburgh
Denton Township
517 366 6888
voshd@voyager.net

Verle Weatherwax
HLIB
6951 E. Houghton Lake Dr
Houghton Lake, MI 48629
989 422 6523

Chip Welling
Minnesota DNR
500 Lafayette Rd., Box 25
St. Paul, MN 55155-4025
651 297 8021
chip.welling@dnr.state.mn.us

Don Winne
MI Lake & Stream Assoc
PO Box 249
Three Rivers, MI 49093-0249
616 273 8200
dwinne@mslwa.org

Appendix B
Working Groups

Biological Control Techniques
Grodowitz (Leader), Newman, Smith, Welling

Chemical Control Techniques
Getsinger (Leader), Bacon, Klemans, McNabb, Poovey, Pullman, Smith

Impacts to Limnology and Watershed
James (Leader), Barko, Bonnell, Klemans, Madsen, McNaught, Welling

Impacts to Fisheries and Wildlife
Maceina (Leader), O'Neal, Pavlovich, Rozich, Valley

Mechanical Control Techniques
Stewart (Leader), Bacon, McNabb, Pullman,

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14. ABSTRACT

Houghton Lake is the largest inland water body in Michigan, and as such, is a major ecological and recreational resource for the region. Results of a survey conducted in October 1999 indicated that over 4,000 ha of the lake had become infested with the exotic submersed plant Eurasian watermilfoil (*Myriophyllum spicatum* L.). Local concern regarding the problems associated with the Eurasian watermilfoil infestation centered on its future impact on recreational opportunities, fish and wildlife resources, and ecological health of the lake. In 2001, the U.S. Army Engineer District, Detroit, was tasked by Congress to assist the Houghton Lake Improvement Board (HLIB) in the development of a draft plan for managing Eurasian watermilfoil on the lake. Therefore, a workshop was held to review operationally viable techniques for managing Eurasian watermilfoil in Houghton Lake, and discuss environmentally sound options for managing this invasive plant. Management options considered included the use of chemical herbicides currently registered in the state of Michigan; the use of the milfoil weevil, a biocontrol agent; the use of mechanical harvesters; and an integration of these techniques. In addition, impacts to water quality and fish and wildlife resources were considered. The objective of this report is to summarize and present information from the workshop and other sources that will provide guidance for the environmentally sound management of Eurasian watermilfoil in Houghton Lake.

15. SUBJECT TERMS

Aquatic plant	Chemical control	Mechanical control
Biological control	Lake management plant	*Myriophyllum spicatum*

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) (Continued)

U.S. Army Engineer Research and Development Center
Environmental Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199;

Eau Galle Aquatic Ecosystem Research Facility
P.O. Box 237, 250th Street @ Eau Galle Dam
Spring Valley, WI 54767;

Department of Fisheries and Allied Aquacultures
Auburn University
Auburn, AL 36849;

Department of Fisheries, Wildlife, and Conservation Biology
University of Minnesota
1980 Folwell Avenue
St. Paul, MN 55108